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SIMULATION AND FLIGHT STUDIES
OF AN APPROACH PROFILE INDICATOR
FOR VTOL AIRCRAFT

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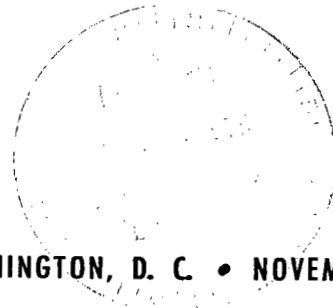
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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • NOVEMBER 1975



0133908

1. Report No. NASA TN D-8051		2. Government Accession No.		3. Recipient's Catalog No.	
4. Title and Subtitle SIMULATION AND FLIGHT STUDIES OF AN APPROACH PROFILE INDICATOR FOR VTOL AIRCRAFT				5. Report Date November 1975	
7. Author(s) Gene C. Moen, Langley Directorate, U.S. Army Air Mobility R&D Laboratory; and Kenneth R. Yenni, Langley Research Center				6. Performing Organization Code	
9. Performing Organization Name and Address NASA Langley Research Center Hampton, Va. 23665				8. Performing Organization Report No. L-10204	
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546				10. Work Unit No. 505-10-23-01	
15. Supplementary Notes				11. Contract or Grant No.	
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				14. Sponsoring Agency Code	
17. Key Words (Suggested by Author(s)) Instrument approach Approach indicator Approach profiles			18. Distribution Statement Unclassified - Unlimited Subject Category 06		
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 44	22. Price* \$3.75		

SIMULATION AND FLIGHT STUDIES OF AN APPROACH PROFILE INDICATOR FOR VTOL AIRCRAFT

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SUMMARY

Simulation and flight investigations were conducted by using a method of providing supplementary information to the pilot in conjunction with a closed-circuit-television display during a VTOL (vertical take-off and landing) instrument final approach including deceleration and hover. The supplementary information included range, cross range, ground speed, altitude, and rate-of-climb error and was displayed on an instrument called an approach profile indicator. The display was arranged to provide both quasi-command and situation information. Pilot comments indicated that the approach-profile-indicator display concept in conjunction with the closed-circuit television resulted in a decreased pilot workload and an increase in pilot confidence. Also, the results indicated that the approach profile repeatability was significantly improved because of the ground-speed and altitude information provided on the approach profile indicator.

INTRODUCTION

The benefits of an out-the-window visual scene are well documented, and the potential benefits of duplicating the real-world scene under instrument conditions are obvious. In practice, however, there are numerous deficiencies in all state-of-the-art real-world display systems. For example, real-world systems are generally two-dimensional, have narrow fields of view, and offer relatively low resolution and contrast. In addition, they do not provide adequate information for flying prescribed VTOL approach trajectories that are desirable from the standpoint of minimizing fuel, noise, and airspace requirements for advanced terminal-area operations. The lack of information was confirmed in a recent flight investigation which used a closed-circuit-television (CCTV) system as a research tool for studying the effects of variations in resolution, field of view, magnification, sensor look angle, and so forth. Unpublished results from that study indicate that the pilots had a tendency to descend and decelerate too late in the approach, which caused periods of high

cockpit workload and implied a requirement for range, altitude, and ground-speed information in order to perform the decelerating approach task in a satisfactory manner.

The purpose of the present investigation was to develop and assess a novel method of providing supplementary information in conjunction with a real-world display. The approach parameters of range, cross range, ground speed, altitude, and rate-of-climb error were displayed in a combined manner on an instrument that is referred to as an approach profile indicator (API). The concept was adopted from a manned spacecraft rendezvous display (ref. 1) and was unique in that the display needles were arranged to provide quasi-command information in addition to situation information. Specifically, when the range, ground-speed, and altitude needles were aligned, the aircraft was on the desired ground-speed and altitude profiles; when the needles were misaligned, the direction and magnitude of the misalignment provided cues to achieve the desired profiles. By combining the information in this manner, the instrument scan problem could be reduced, which effectively would reduce the pilot workload.

Simulated instrument approaches and hovers using the API in conjunction with a CCTV display were conducted on a fixed-base simulator and on a single-rotor helicopter. The purpose of this paper is to describe the API display concept and to present the results of the simulator and flight tests.

SYMBOLS

The units used for physical quantities defined in this paper are given in both the International System of Units (SI) and U.S. Customary Units. The measurements and calculations were made in U.S. Customary Units. Factors relating the two systems are given in reference 2.

a	constant in range channel, $m^{1/2}/sec$ ($ft^{1/2}/sec$)
b	constant in range channel, m (ft)
c	constant in range channel, m/sec (ft/sec)
d	constant in altitude channel, $m^{1/2}/sec$ ($ft^{1/2}/sec$)
h	altitude, m (ft)
k_1, k_2, k_3	scale attenuation constants (defined in appendix C)

x,y,z position coordinates in rectangular coordinate system (fig. 4), m (ft)

γ glide slope, deg

Subscripts:

e error

f final condition for variable

fs meter full-scale value for variable

o initial condition for variable

A dot over a quantity indicates the first derivative with respect to time. Two dots over a quantity indicate the second derivative with respect to time.

Single and double primed quantities indicate the signal processing input and output voltages, respectively.

DESCRIPTION OF EQUIPMENT

Approach Profile Indicator

The API, shown in figure 1, consisted of five edge-reading meters which were mounted in a cluster directly below the CCTV display in both the simulator (fig. 2) and the flight vehicle (fig. 3). The top meter provided the pilot with an indication of linear cross-range errors with respect to the extended runway center line. The remaining four meters were vertically mounted and presented (from left to right) rate-of-climb error, altitude, range, and ground speed along the extended runway center line. The coordinate system containing these parameters is shown in figure 4. The altitude, range, and ground-speed meters were marked to provide situation information and provided low-gain, quasi-command information to the pilot. In its use as a quasi-command indicator, the range meter was considered to be the primary indicator, and the pilot's task was to control the ground speed and altitude in a manner which resulted in aligning these two needles with the range needle.

The range, altitude, and ground-speed scales (fig. 1) were selected to correspond to nonlinear altitude and ground-speed profiles, which are described in a subsequent section. The nonlinear signal processing was done with analog computer components, which were packaged as shown in figure 5. Variations in the ground-speed profile were obtained by rescaling the linear ground-speed meter. The four ground-speed profiles (fig. 6) were investigated on the fixed-base simulator, and one profile was selected for flight evaluation.

The rate-of-climb-error meter differed from the other meters in that it did not directly provide situation information to the pilots. This meter was driven by a special error function which, in effect, slaved this needle to the altitude needle. Specifically, a rate-of-climb error caused the needle either to lead (if the sink rate was too high) or lag the altitude needle (if the sink rate was too low), and a proper rate of climb to maintain the prescribed altitude profile would result in the needles being aligned. The sensitivity of the error signal was selected to provide a 2.5-cm (1-in.) separation of the needles for a 150-m/min (500-ft/min) sink rate error.

Simulator Description

Initial tests were conducted on a fixed-base, VTOL simulator which consisted of a cockpit, a landing terrain scene generator (LTSG), and a CCTV system for presenting a real-world scene to the test subject. Included in the cockpit (fig. 2) were the API, simulated helicopter controls, panel-mounted displays, 63.5-cm (25-in.) CCTV monitor, and virtual image lens. The edges of the CCTV monitor were masked to simulate the 35.6-cm (14-in.) CCTV monitor used in the flight vehicle. The monitor was installed with the long axis of the cathode ray tube (CRT) vertical in order to obtain an increased vertical field of view. One difference between the simulator and flight-vehicle cockpit was the virtual image lens, which allowed the pilot's eyes to be focused at infinity. The cockpit was shared with other simulation programs requiring the lens, and it was not practical to remove and replace the lens on an intermittent basis. It was believed, however, that this feature would not significantly affect the results of the study. The visual scene was obtained from the six-degree-of-freedom LTSG shown in figures 7 and 8. Elements of the LTSG included a CCTV camera, a servo-carriage system, and a 1/300-scale model airport.

The helicopter mathematical model used in the simulation is presented in reference 3. The equations of motion were solved in a Control Data 6600 computer system which provided signals through a digital-analog interface for driving both the API and LTSG.

Flight Equipment

The single-rotor helicopter, shown in figure 9, was used as the flight-test vehicle. This helicopter was equipped with production automatic stabilization equipment (ASE). Two channels of the ASE provided attitude stabilization about the respective pitch and roll axes. A third channel, which was slaved to the compass system, provided yaw-rate damping and a heading-hold feature.

A high-resolution (946 scan lines), black-and-white CCTV system was installed on the aircraft. The camera was located on the left side of the aircraft nose and had a depressed look angle of 5° with respect to the helicopter longitudinal axis. The camera

zoom lens was set for a 29° field of view, which provided a unity magnification at the CCTV display. The 35.6-cm (14-in.) monitor was located 68 cm (27 in.) from the test subject's eyes and was installed so that the longest dimension of the CRT was vertical. The selection of the electro-optical parameter values for field of view, magnification, aspect ratio, and so forth, was based on the results of a prior CCTV display study.

In addition to the CCTV display, the evaluation pilot's (test subject's) instrument panel (fig. 3) included the API and three additional vertical strip instruments located peripherally around the monitor. The three strip instruments provided the test subject with airspeed, rate-of-climb, and radio-altitude information. Although these three strip instruments were active, pilot comments indicated that they did not use them when the API was used. Curtains were placed around the evaluation pilot's station to simulate an instrument flight condition.

A ground-based precision radar was used to track the helicopter and provided the position and velocity signals to the API. A description of the radar is contained in appendix A.

PILOT'S TASK

The task was to take control of the helicopter (or simulator) and fly a descending, decelerating approach from a predetermined set of initial conditions and using prescribed speed and altitude profiles, terminating in a 12-m (40-ft) hover over a landing pad. The initial part of the task varied slightly, depending on whether the approaches were flown in the fixed-base simulator or the helicopter. In the simulator, all approaches were started from fixed initial conditions; specifically, range of 3.04 km (10 000 ft), altitude of 274 m (900 ft), and ground speed of 80 knots. The task was to continue the approach, holding the initial conditions for altitude and ground speed until the range needle matched the altitude needle. At that point, the pilot initiated the letdown along the glide slope, holding the ground-speed initial condition until the range needle matched the ground-speed needle. From that point on, the task was to control the altitude and ground speed in a manner to maintain alinement of the respective needles with the range needle until the hover condition was achieved (zero range and ground speed, 12-m (40-ft) hover).

In the flight program, the initial conditions were set up by the safety pilot who controlled the aircraft on the downwind leg and initiated the base turn. During the base turn, the test subject was given control of the aircraft which had a nominal initial condition of 243 m (800 ft) altitude, 80 knots airspeed, and a range in excess of 2 nautical miles. After taking control of the aircraft, the pilot's task was to continue the base turn, holding the altitude and airspeed initial conditions until he made visual contact with the runway by means of the CCTV display. After making visual contact with the runway, he then continued the approach in the same manner as in the simulation task.

The approaches flown without the API had a different task definition. Without the API, there was no precision guidance information for the test subject; therefore, the task was to fly a descending, decelerating approach which felt "comfortable," using the information from the CCTV display and the three peripheral instruments.

PROFILES

The ground-speed profiles which were investigated are shown in figure 6. In the API concept, each profile represents a different scale factor on the ground-speed meter and is defined by the following equation:

$$\dot{x} = a\sqrt{x + b} + c \quad (1)$$

where \dot{x} is in m/sec (ft/sec). Equations for determining the constants a , b , and c are derived in appendix B. Equation (2) defines the corresponding deceleration profiles (fig. 10) associated with each of the ground-speed profiles. This equation is obtained by differentiating equation (1) and by substituting equation (1) into the differentiated expression to give

$$\ddot{x} = \frac{a^2}{2} \left(1 - \frac{\sqrt{b}}{\sqrt{x + b}} \right) \quad (2)$$

where \ddot{x} is in m/sec² (ft/sec²).

Although an infinite number of possible ground-speed profiles exist, equation (1) was found to provide an acceptable deceleration profile and to contain several desirable features for programing the API concept. First, the deceleration profiles defined by equation (2) feature a gradually decreasing deceleration level. This characteristic is similar to a constant-attitude-type deceleration profile. Flight-test results (ref. 4) indicate that deceleration profiles which require a nearly constant attitude throughout the approach are readily accepted by pilots and provide an easier pilot task during the final transition to hover. In addition, the shape of the ground-speed profile permits an increasing display sensitivity, which is quite desirable for controlling range and altitude as the helicopter gets closer to the pad.

The API altitude profile (fig. 11) intercepts the 6° reference slope at range values of zero and 3.04 km (10 000 ft) and exhibits a slight concave-up characteristic. This profile was selected because it approximates a 6° straight-line glide slope, which has been used for a number of VTOL instrument approach studies, and because of the concave-up feature, which is characteristic of VFR approaches. Equations for the altitude profile and signal processing are given in appendixes B and C, respectively.

RESULTS AND DISCUSSION

Fixed-Base Simulation

One hundred and eleven approaches were flown on the fixed-base simulator using four NASA research pilots as test subjects to investigate the CCTV display by itself and the CCTV display with the API programed for four different ground-speed profiles. A summary of the display configurations, together with the number of approaches flown by each test subject, is shown in the following table:

Display configuration	Data runs made by test subject –				Total data runs
	A	B	C	D	
CCTV only		6	6	6	18
140-knot ground-speed profile (API and CCTV)	15	9		9	33
120-knot ground-speed profile (API and CCTV)		10		7	17
110-knot ground-speed profile (API and CCTV)			8	6	14
100-knot ground-speed profile (API and CCTV)	14	8		7	29
Total	29	33	14	35	111

During each approach, the profile variables of altitude, ground speed, and cross range were recorded as a function of range. These profile plots were then processed to obtain arithmetic average values and standard deviations at selected range intervals. For the purpose of the study, the arithmetic averages provided an indication of how well the test subjects tracked a particular parameter, and the standard-deviation envelopes provided an indication of the test subjects' repeatability in performing the task. The data were processed first to obtain the composite results from all test subjects for each display configuration. After obtaining the composite results, the data from the baseline test subject were then processed to obtain the comparative results from an individual test subject. Test subject D was chosen as the simulation baseline test subject because he flew all test cases.

The simulation results are presented in figures 12 to 17. Clearly, it is not particularly instructive to directly compare the results from the combination display (CCTV and API) (figs. 12 to 14) with the results for the CCTV only (fig. 15) because the two displays were flown using different tasks. However, in reviewing the results, some general observations can be made. Specifically, with the combined display (CCTV and API), the standard-deviation envelopes for the ground-speed and altitude profiles were significantly smaller throughout the approach and demonstrated a smooth convergence

toward the parameter hover value (e.g., 12-m (40-ft) altitude and zero ground speed). A comparison of figures 14, 15(e), and 15(f) indicates that the API did not improve pilot performance in controlling the cross-range parameter. Test subjects' comments indicated that they preferred to use the real-world display for controlling cross-range position rather than to use the cross-range meter on the API. In short, the real-world display presented a more compelling cross-range-error cue to the test subjects than did the cross-range meter. In addition, the test subjects commented that errors in cross range did not demand immediate and accurate correction because they could extrapolate a correction and determine from the real-world display that they would be on the correct cross-range track in time to complete the approach.

The simulation results were further analyzed to determine the average standard deviation for each of the envelopes shown in figures 12 to 15. The area of each standard-deviation envelope was measured with a planimeter and the average standard deviation was computed by dividing the resulting area by the range involved with the test.

The average standard-deviation results are shown in bar-graph form in figures 16 and 17. The bar graphs on the left represent the average standard-deviation values of that parameter for the entire approach (2896 m (9500 ft)), and the bar graphs on the right represent the same values averaged over the last 914 m (3000 ft) of the approach. The obvious results shown in these figures are that the ground-speed and altitude information provided by the API significantly improved the test subjects' repeatability. Furthermore, the results indicate that the information provided by the cross-range meter was of no benefit in performing the task and confirm the test subjects' comments that the cross-range meter was not used by them during the approach. These results also indicate that the best overall repeatability was obtained when the API was configured for the 110-knot ground-speed profile.

Flight Program

A total of 40 approaches were flown by two NASA research pilots and one U.S. Navy test pilot. Of these approaches, 32 were flown using the combination display (CCTV and API) configured for the 100-knot ground-speed profile, and the remaining 8 approaches were flown by test subject A, using the CCTV display only. Only one ground-speed profile (100 knot) was flight tested on the API because of flight-time limitations imposed on the aircraft by the primary research program. The selection of this profile was based on the simulator test subjects' comments that the 100-knot profile was the easiest and most gentle profile to control in the simulator. A summary of the flight tests is shown in the following table:

Display configuration	Data runs made by test subject -			Total data runs
	A	B	E	
CCTV only	8	0	0	8
100-knot ground-speed profile (API)	17	7	8	32

The flight-test data were processed in a manner similar to that used for the simulation data. Arithmetic-average and standard-deviation values are shown in figures 18 to 20. These results are based on data from individual test subjects instead of combining the data from all test subjects as was done with the simulation results.

Test subject A was the assigned project pilot on a prior research program and, as such, had flown approximately 300 approaches which used the CCTV display only. Thus, his results in this study represent the results from a test subject who was highly trained with the basic CCTV display system. A comparison of the average-standard-deviation values (figs. 21(a) and 21(b)) shows that test subject A's repeatability improved from 20 to 60 percent with the combination display.

Test subject B had no recent experience with CCTV displays except for 33 approaches flown in the simulator. As a result of his simulation experience with the combination display, test subject B requested that he be permitted to use a modified task during the flight program. His suggested task modification, which he was permitted to use, was to let the ground-speed needle lag the range needle by approximately 10 knots of ground speed. This task modification resulted in a higher average ground speed, as shown in figure 19(c). Even though the task modification was supposed to apply only to controlling the ground-speed profile, the results indicated (fig. 18(c)) that test subject B also lagged the altitude needle, which in turn resulted in a higher arithmetic average for the glide-slope parameter. This task modification, however, demonstrated an operational flexibility in piloting techniques which can be used with the API concept.

Test subject E was a Navy test pilot, highly trained in the aircraft type, but he had no prior experience with either real-world displays or the API. His results were consistent with the results from the other test subjects except for the ground-speed profile during the last 200 m (650 ft) of the approach. This is the region in the approach where the aircraft is in transition to the hover condition, and the standard-deviation envelope does not indicate a smooth convergence of the ground-speed parameter during this transition period. This is also the region in which the test subject's concentration shifted from the API to the real-world display, and the lack of smooth convergence is probably indicative of the test subject's lack of prior flight training with real-world displays.

The cross-range results (fig. 21(c)) confirm the simulation results wherein the cross-range meter did not improve pilot performance in controlling the cross-range parameter.

Flight tests without the API were conducted under near-calm wind conditions; whereas, the flight tests with the combination display were conducted with head winds varying from 12 to 24 knots and from directions varying 45° to -45° relative to the runway heading. All approaches were initiated at 80 knots indicated airspeed, and the head winds caused a corresponding reduction in the value of the ground-speed initial conditions. In most cases, the test subjects continued the approach at the reduced value of ground speed until they intercepted the programmed speed profile. The pilots commented that this characteristic in itself did not cause a piloting problem.

SUMMARY OF PILOT COMMENTS

All test subjects commented that the API significantly reduced the pilot workload and increased pilot confidence during the approach. They also indicated that the API provided an effective means for flying predetermined ground-speed and altitude profiles with a relatively high degree of repeatability. All test subjects in the flight-test program indicated that the 100-knot ground-speed profile was too slow and resulted in coming to a near-hover condition too far from the landing pad. They also thought that a faster ground-speed profile would have eliminated this problem. (The simulation results indicated that the 110-knot profile would be better.)

In all cases, the test subjects preferred not to use the cross-range meter for cross-range position cues. Instead, their preference was to obtain the cross-range information from the CCTV display. The probable reason for this comment was that the cross-range cues were far more compelling on the real-world display than the corresponding cues from the cross-range meter.

All test subjects indicated that, throughout most of the approach, their primary concentration was on the API; but, during the final stages of the approach, their concentration shifted to the CCTV display. Their estimate was that approximately 80 percent of their concentration was devoted to the API, with the remaining 20 percent devoted to the CCTV until they approached the hover condition, at which point the percentages of concentration reversed to 80 percent on the CCTV and the remaining 20 percent on the API.

CONCLUSIONS

An evaluation has been conducted on an electromechanical display that provides supplementary approach profile information in conjunction with a closed-circuit-television

display. The approach profile indicator was designed to provide both situation and quasi-command information to aid the pilot in performing an instrument final approach and hover task in a VTOL aircraft. From the simulation and flight tests, the following conclusions are indicated:

1. The approach profile indicator, when used in conjunction with a real-world display, reduced the pilot's workload and increased the pilot's confidence.

2. Approach profile repeatability was significantly improved because of the ground-speed and altitude information provided on the approach profile indicator.

3. The concept of structuring situation information to obtain quasi-command information provided a desirable operational flexibility in the piloting techniques used during the VTOL approach task.

4. The cross-range information provided on the approach profile indicator was not used by the evaluation pilots because the same information was more easily derived from the closed-circuit television and, as such, should be deleted from the approach-profile-indicator concept when used in conjunction with a real-world display.

5. In flight, the 100-knot ground-speed approach profile resulted in too slow an air-speed at the hover transition point and increased the approach time unnecessarily. Pilot comment strongly indicated that a faster ground-speed profile would be a significant improvement. The simulation results, which included 110-knot profiles, support these comments.

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September 24, 1975

APPENDIX A

DESCRIPTION OF TRACKING RADAR

The GSN-5 precision tracking radar measures the position of aircraft in terms of slant range, azimuth, and elevation angles of the radar antenna. Data from this spherical coordinate system are transformed into the rectangular coordinate system shown in figure 4. Transformed aircraft data – both positions and rates – are transmitted to the aircraft on a narrow-band, frequency-modulated (FM) telemetry link. A passive corner reflector was mounted on the nose of the aircraft to prevent skin tracking.

The GSN-5 is a K-band radar and has an antenna beam width of approximately 0.5° . This radar is capable of tracking from 0° to 30° in elevation and from 45° to -45° in azimuth. Position uncertainties in rectangular coordinates are shown in the following table:

Range		Position uncertainty in coordinate –					
		x		y		z	
km	ft	m	ft	m	ft	m	ft
0	0	5	16.4	1	3.28	1	3.28
4	13 150	36	118	2.5	8.2	3.2	10.5

APPENDIX B

PROFILE EQUATIONS

Equation (1), which defines the nominal ground-speed profiles, is repeated for convenience as follows:

$$\dot{x} = a\sqrt{x + b} + c$$

where \dot{x} is in m/sec (ft/sec).

The constant b is a range offset distance (fig. 4) and is defined by the following equation:

$$b = \frac{h_f}{\tan \gamma_0} \quad (B1)$$

and is measured in m (ft).

For the hover condition, \dot{x} must equal zero when $x = 0$. It follows, therefore, that

$$c = -a\sqrt{b} \quad (B2)$$

in m/sec (ft/sec).

Furthermore, the matching of the x and \dot{x} needles at full scale dictates that:

$$\dot{x}_{fs} = a\sqrt{x_{fs} + b} + c$$

Substituting for c and solving for a yields

$$a = \frac{\dot{x}_{fs}}{\sqrt{x_{fs} + b} - \sqrt{b}} \quad (B3)$$

in $m^{1/2}/\text{sec}$ ($ft^{1/2}/\text{sec}$).

After developing the signal processing equations (appendix C), a mathematical relationship was developed which describes the altitude profile shown in figure 11. This relationship, which is valid over the region of interest ($x = 0$ to $x = x_{fs}$), is defined by the following equation:

APPENDIX B

$$z = A(x - 2\sqrt{b}\sqrt{x+b} + 2b) + h_f \quad (B4)$$

where z is given in m (ft) and

$$A = \frac{x_{fs} \tan \gamma_o}{x_{fs} - 2\sqrt{b}\sqrt{x_{fs}+b} + 2b} \quad (B5)$$

The family of ground-speed profiles (fig. 6) and the altitude profile (fig. 11) were obtained by plotting equations (1) and (B4), respectively, for the following conditions:

$$h_f = 12.2 \text{ m (40 ft)}$$

$$\gamma_o = 6^\circ$$

$$x_{fs} = 3.046 \text{ km (10 000 ft)}$$

$$\dot{x}_{fs} = 100, 110, 120, \text{ and } 140 \text{ knots}$$

APPENDIX C

SIGNAL PROCESSING

The position and velocity signals received onboard the aircraft from the ground-based radar were voltages that were proportional (linear) functions of the measured parameters. In formulating the display concept, analog circuits (fig. 22) were developed for processing these proportional signals into a proper format for displaying the respective parameters on the API.

Each circuit represents the signal processing used for that specific channel, and it should be pointed out that each channel (except for the rate-of-climb-error channel) functioned independently of the remaining channels. Specifically, the signal processing problem was to shape the output signals in a manner such that, when the aircraft was on the prescribed profiles, the needles would be aligned on the API.

Ground-Speed Channel

Because of display sensitivity considerations, the ground-speed parameter was displayed on the API as a linear function of measured ground speed. Therefore, the signal processing equation for this channel (fig. 22(a)) was

$$\dot{x}^* = \left(\frac{100}{\dot{x}_{fs}} \right) k_1 \dot{x} \quad (C1)$$

where \dot{x}^* denotes the meter displacement in percent of full scale and k_1 is a scaling constant.

Range Channel

Since the ground-speed parameter was displayed as a linear function, the range signal was processed to obtain the nonlinear ground-speed profiles defined by equation (1). The signal processing equation for the range channel (fig. 22(b)) was

$$x^* = \left(\frac{100}{x_{fs}} \right) (a \sqrt{x + b} + c) \quad (C2)$$

where x^* denotes the range meter deflection in percent of full scale.

Altitude Channel

The selection of the signal processing equation for the altitude channel was based on a desire to approximate a straight-line glide slope, which meant that the altitude equation

APPENDIX C

should be of the same general form as equation (C2). During bench tests, it was discovered that the signal processing equation given next, in addition to approximating a straight-line glide slope, would result in a slightly concave-up altitude profile which approximated a similar characteristic found in VFR altitude profiles.

The signal processing equation for the altitude channel (fig. 22(c)) was

$$z^* = \left(\frac{100}{\sqrt{x_{fs}} \tan \gamma_o} \right) d \sqrt{z - h_f} \quad (C3)$$

where z^* denotes the altitude meter deflection in percent of full scale.

Rate-of-Climb-Error Channel

The signal processing equation for the rate-of-climb-error channel (fig. 22(d)) was

$$\dot{h}^* = z'' + k_2 \dot{h}_e \quad (C4)$$

where \dot{h}^* denotes meter deflection in terms of cm/(m/min) (in/(ft/min)) rate-of-climb error and where

$$\dot{h}_e = \left(\dot{z} - \tan \gamma_o \dot{x} \right) \quad (C5)$$

in m/sec (ft/sec).

The z'' term, which is the output voltage from the altitude channel, is used to slave the rate-of-climb-error needle with the altitude needle. The constant k_2 represents a potentiometer for adjusting the display sensitivity (e.g., 150-m/min (500-ft/min) sink-rate error was approximately equal to a 2.5-cm (1-in.) separation of the two respective needles).

Cross-Range Channel

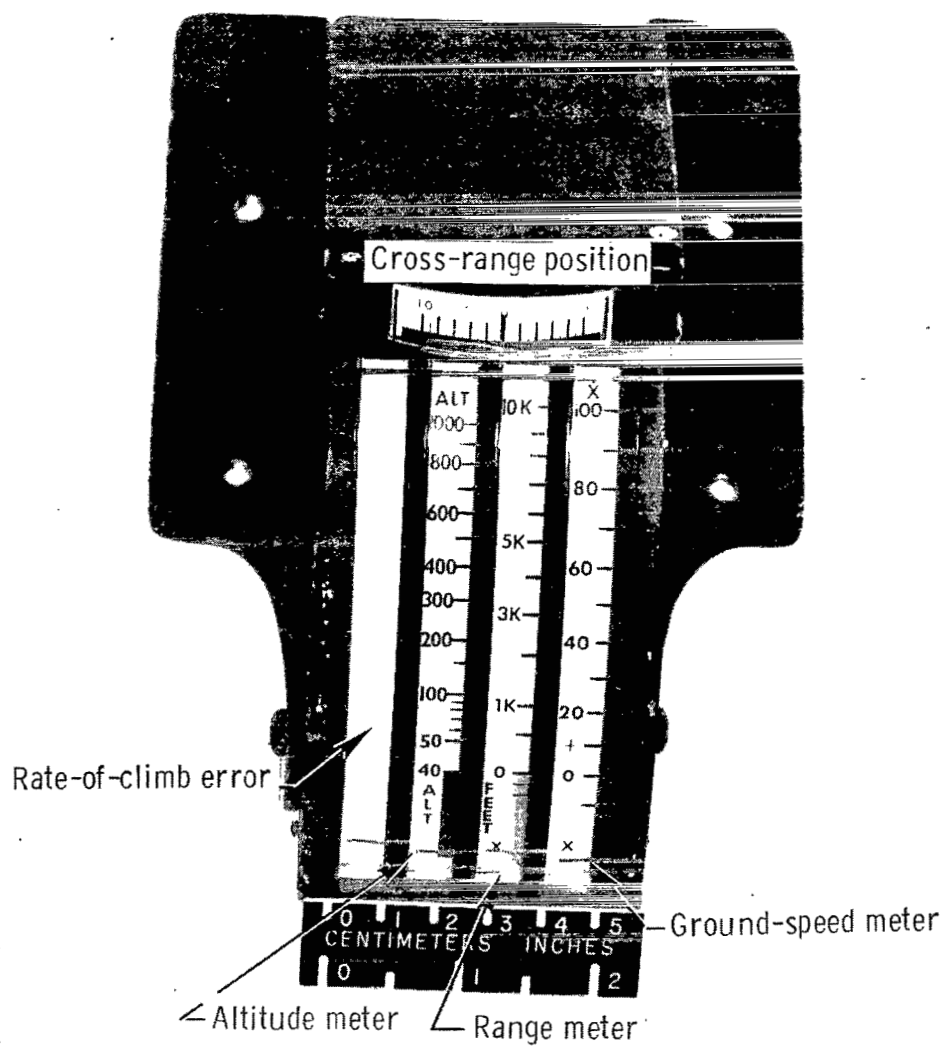
The signal processing equation used in the cross-range channel (fig. 22(e)) was

$$y^* = \left(\frac{100}{y_{fs}} \right) k_3 y \quad (C6)$$

where y^* denotes the cross-range meter deflection in percent of full scale and k_3 is a scaling constant.

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3. Houck, Jacob A.; Gibson, Lucille H.; and Steinmetz, George G.: A Real-Time Digital Computer Program for the Simulation of a Single-Rotor Helicopter. NASA TM X-2872, 1974.
4. Kelly, James R.; Niessen, Frank R.; Thibodeaux, Jerry J.; Yenni, Kenneth R.; and Garren, John F., Jr.: Flight Investigation of Manual and Automatic VTOL Decelerating Instrument Approaches and Landings. NASA TN D-7524, 1974.



L-74-2470

Figure 1.- Approach profile indicator.



Figure 2.- Simulator cockpit.

L-74-5324

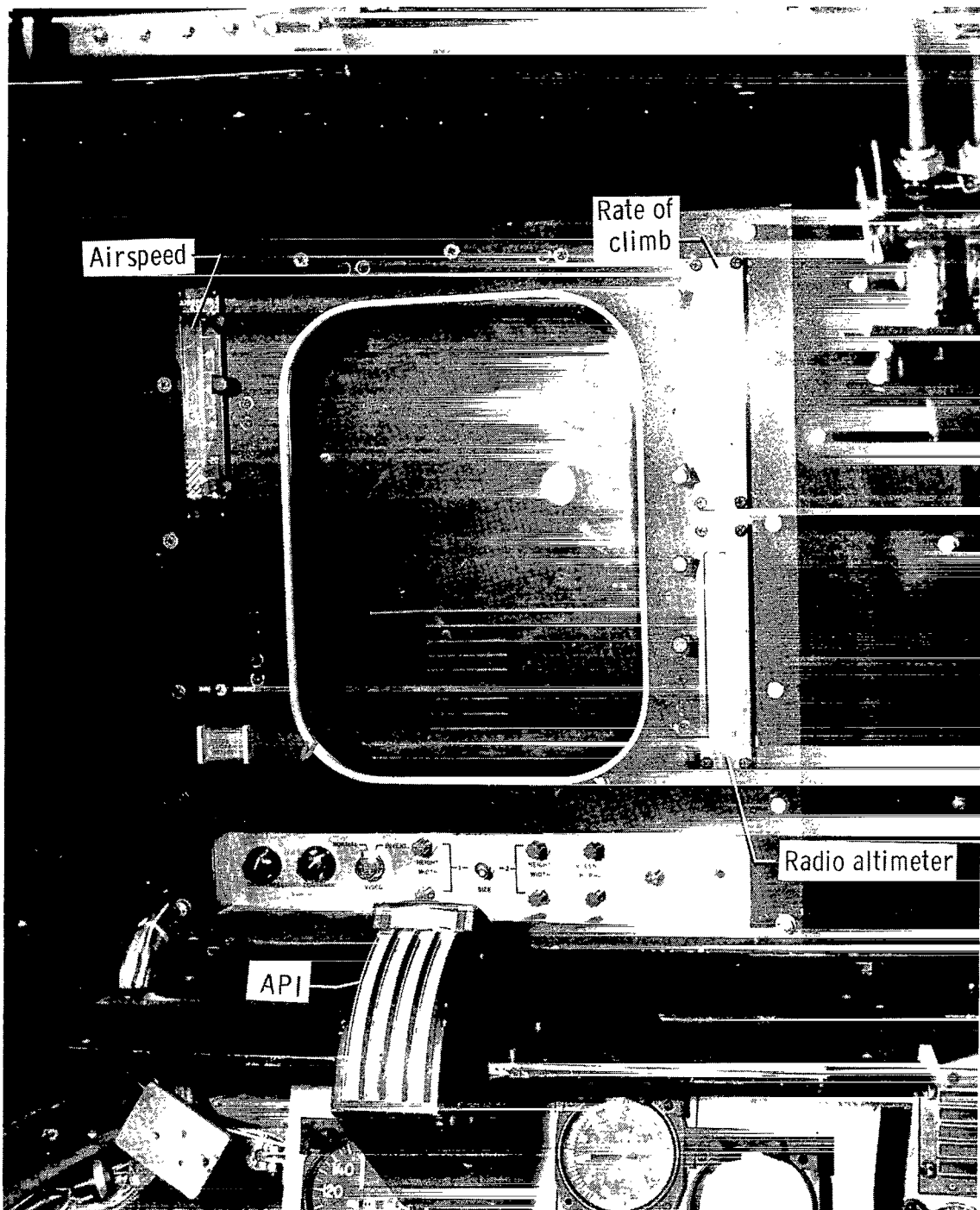


Figure 3.- Helicopter cockpit.

L-74-2313

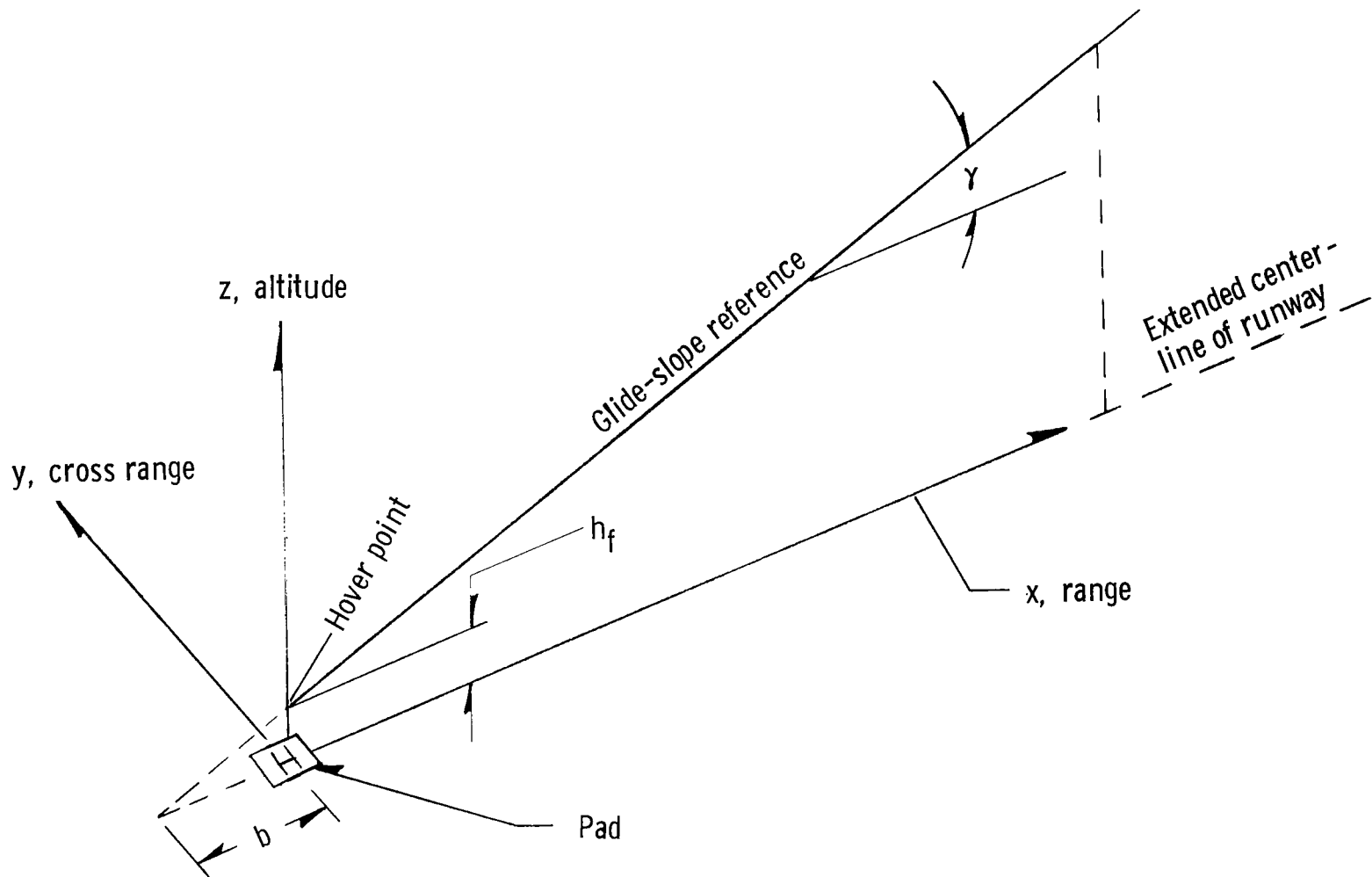
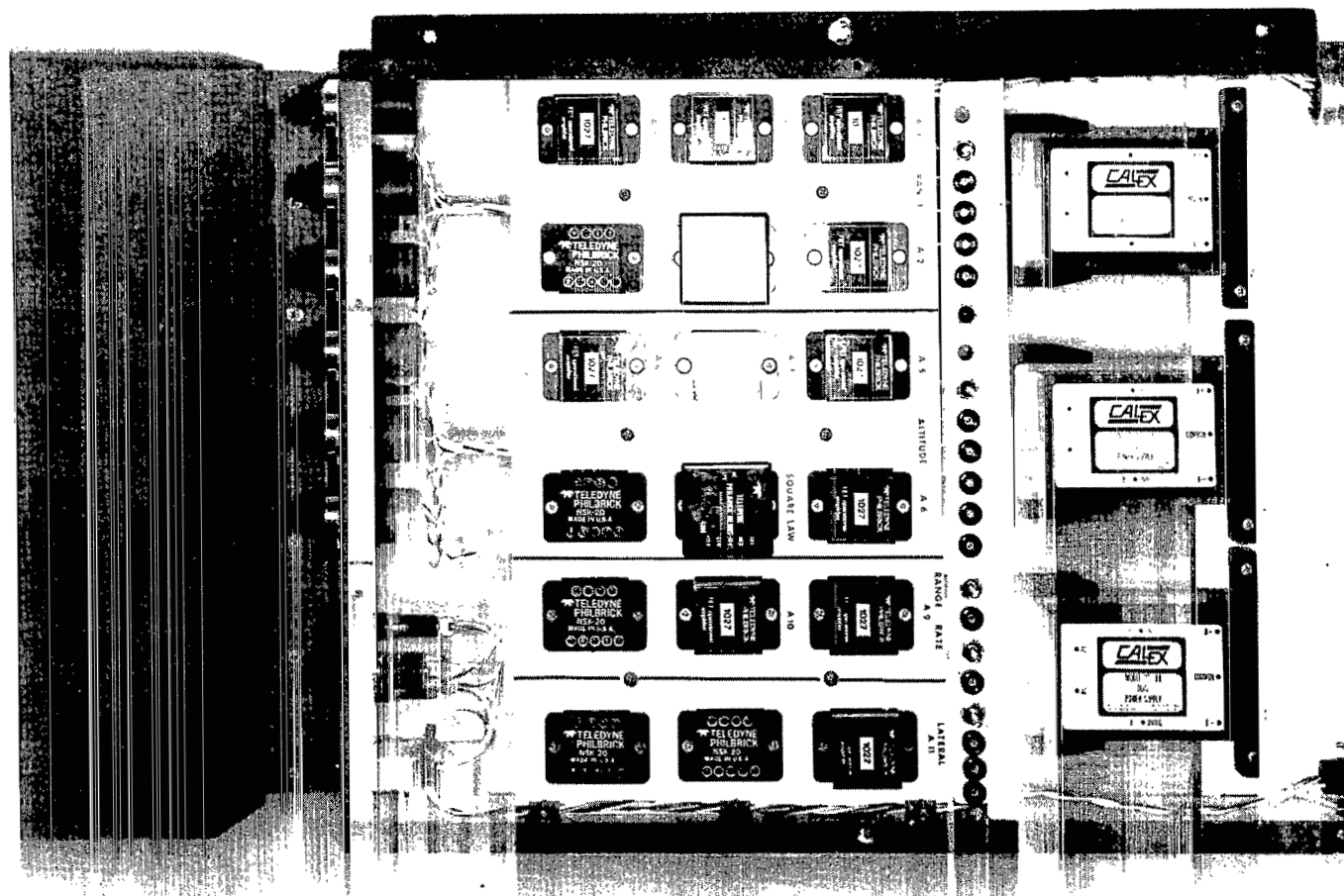


Figure 4.- Approach coordinate system.



L-73-7122

Figure 5.- Signal conditioning box.

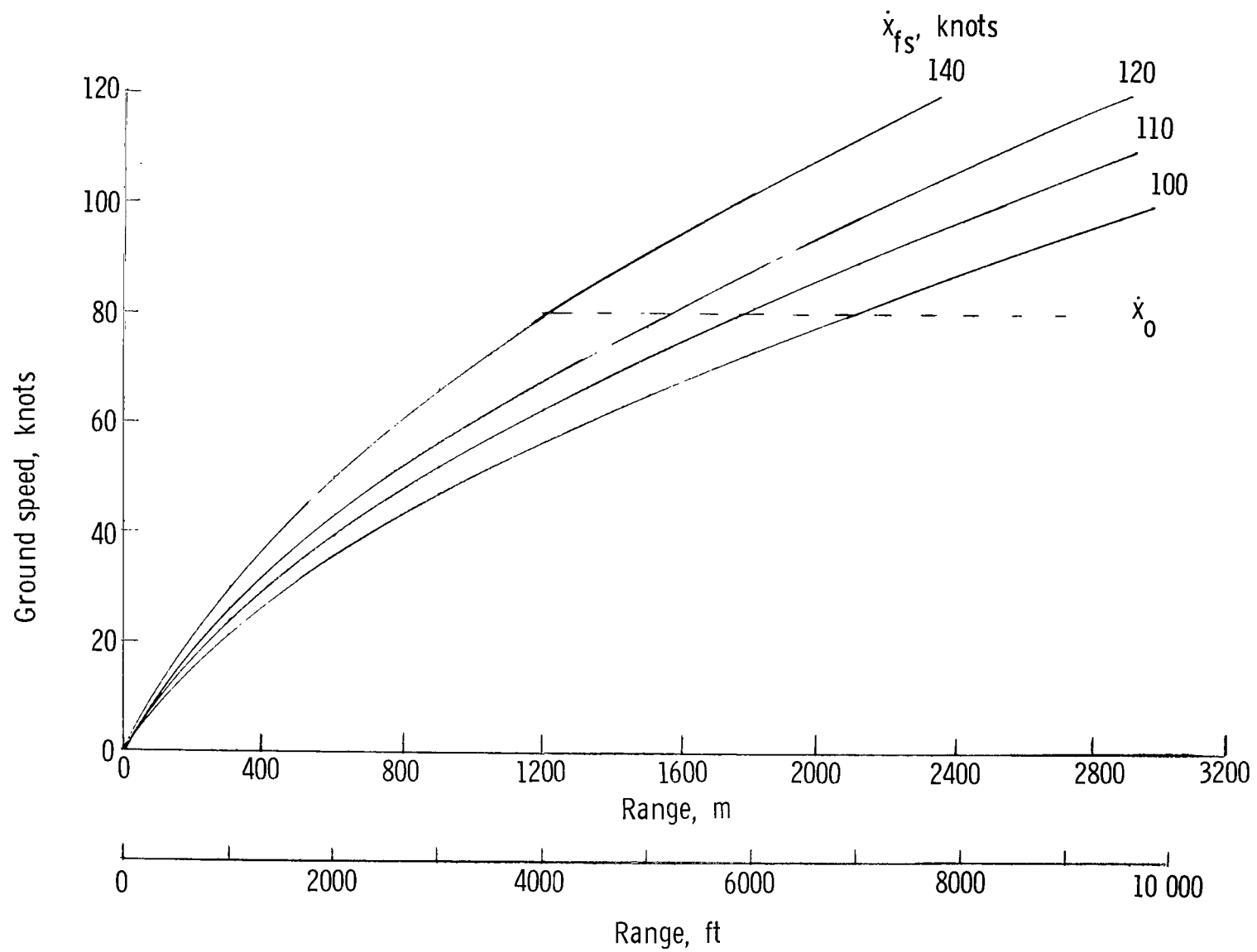
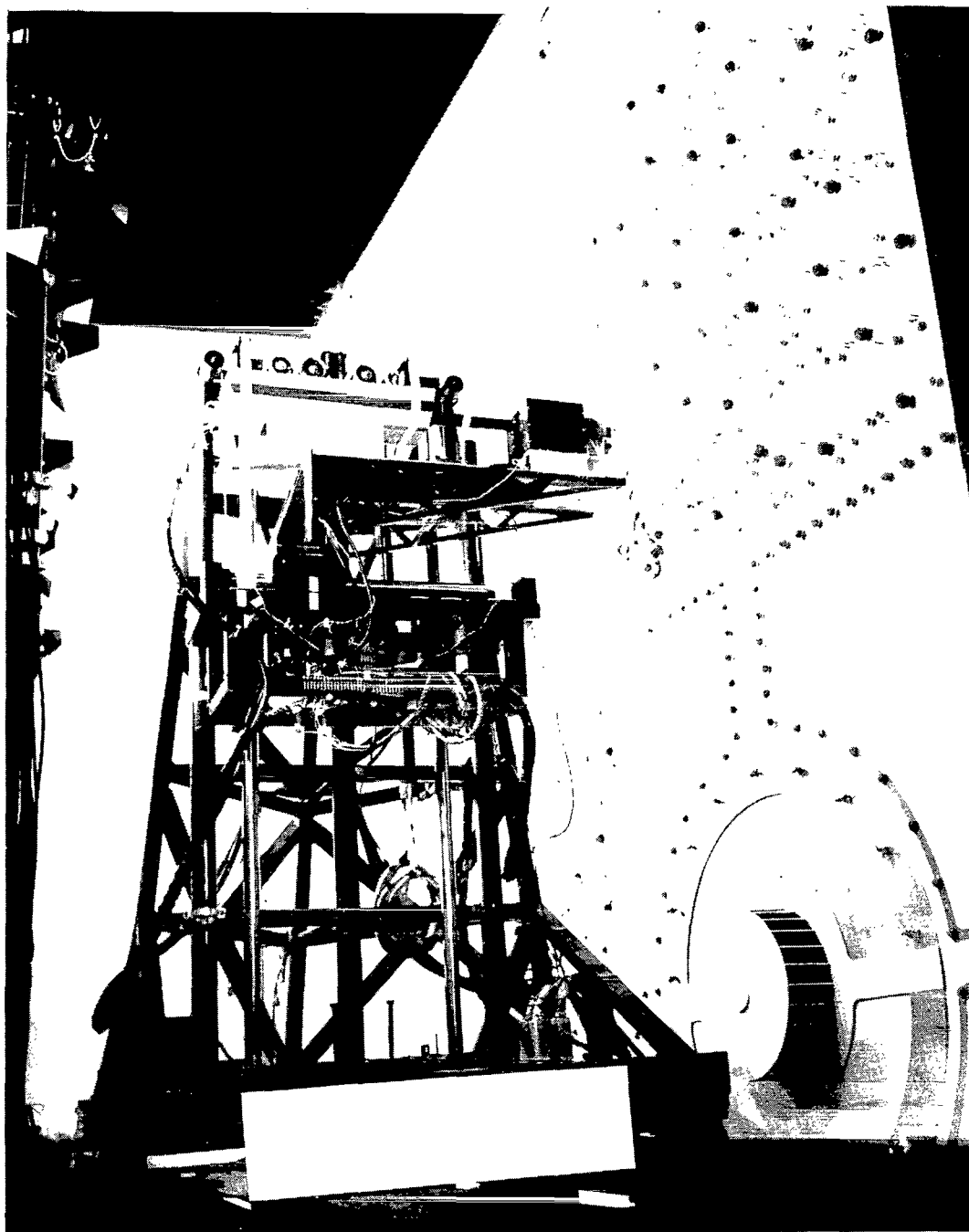


Figure 6.- Ground-speed profiles for 6° glide slope.



L-70-5683

Figure 7.- Landing terrain scene generator.

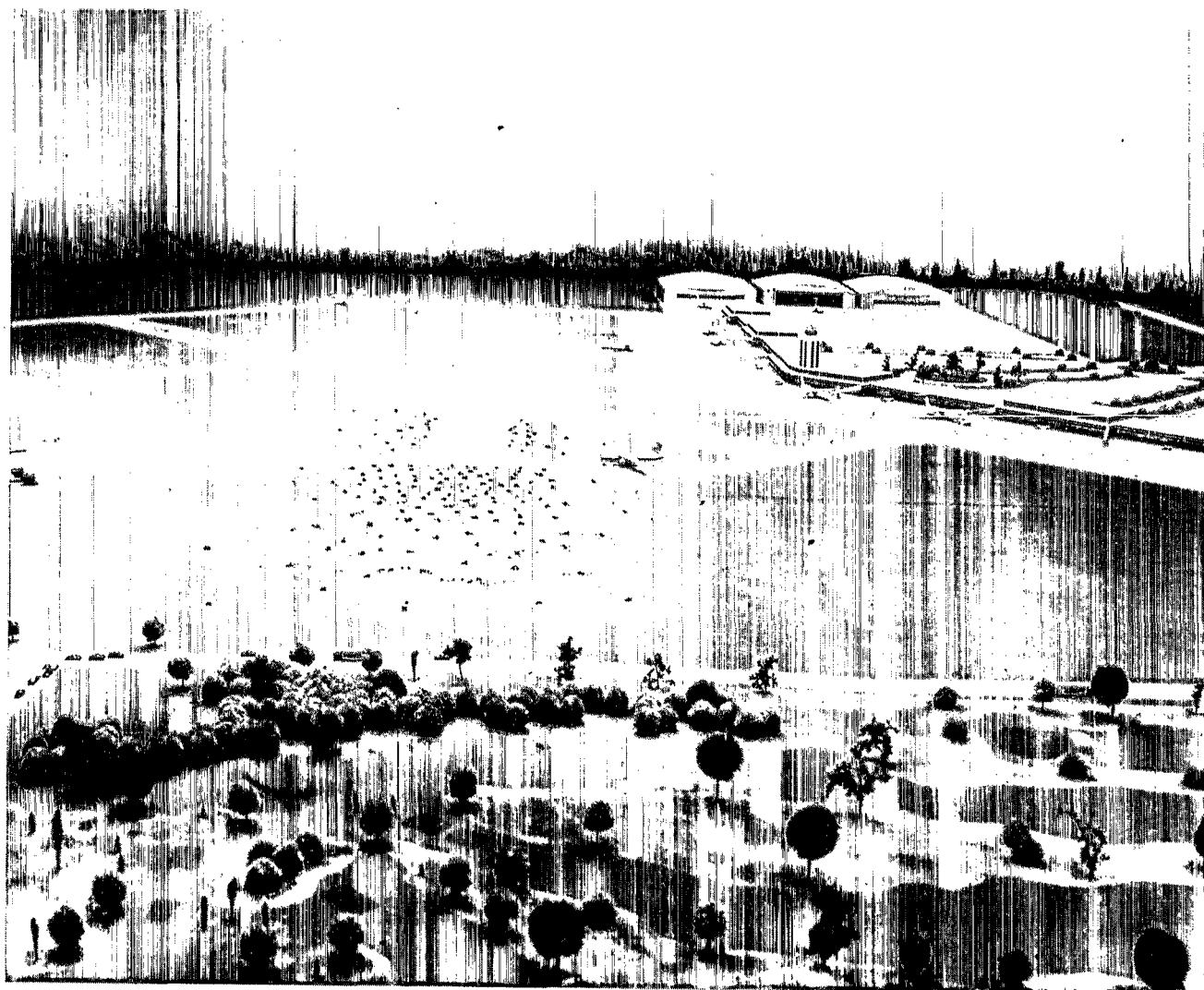


Figure 8.- Airport scale model.

L-70-5684



Figure 9.- Test vehicle.

L-72-4918

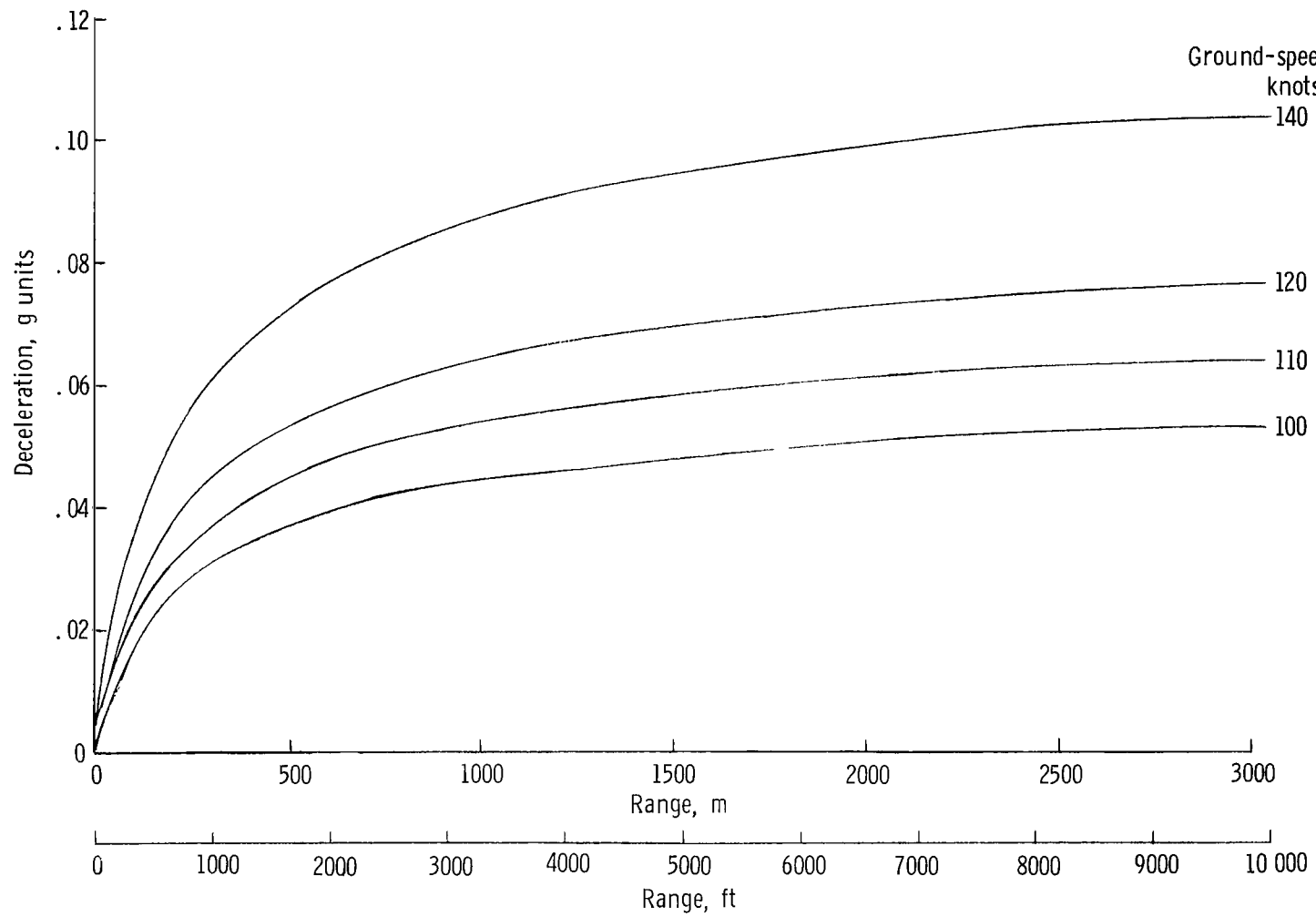


Figure 10.- Deceleration profiles.

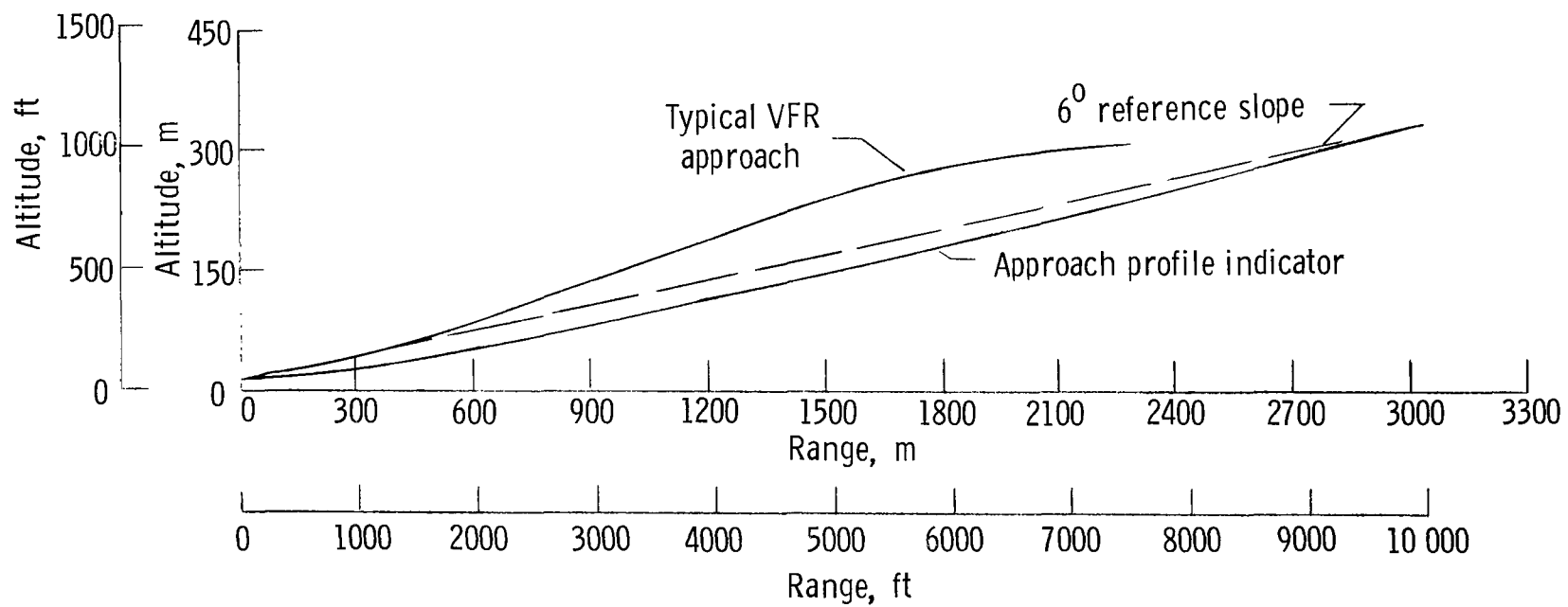
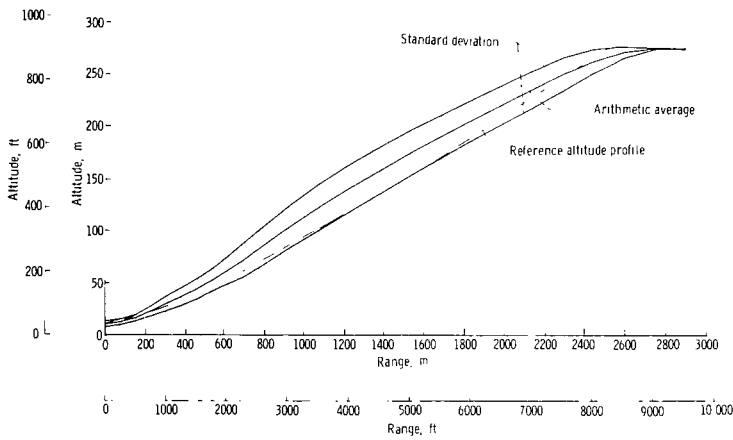
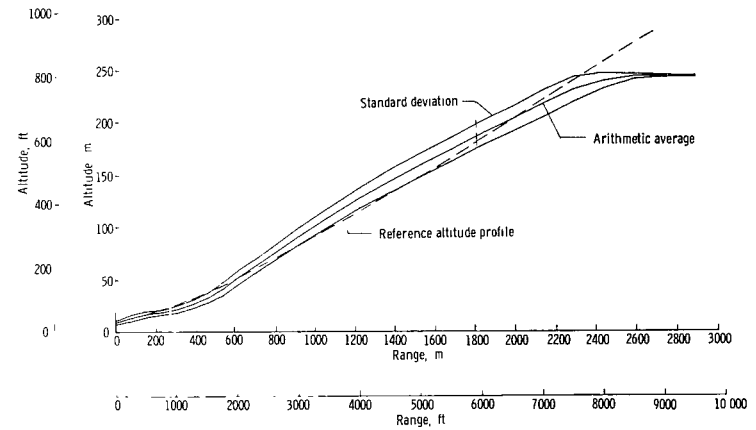


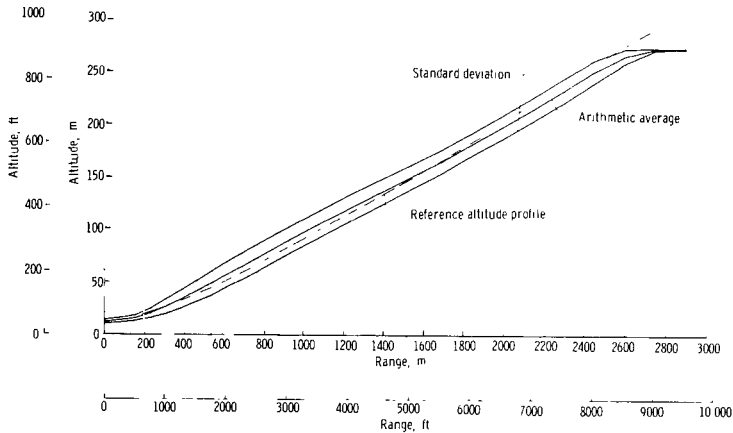
Figure 11.- Altitude profiles.



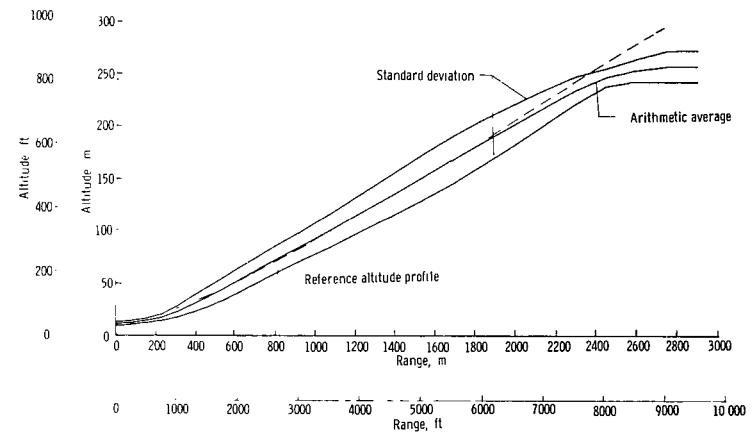
(a) All pilots, 100-knot ground-speed profile.



(b) All pilots, 110-knot ground-speed profile.

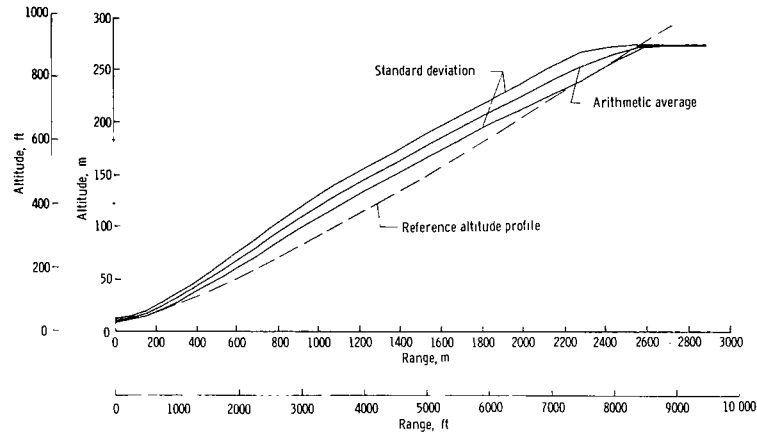


(c) All pilots, 120-knot ground-speed profile.

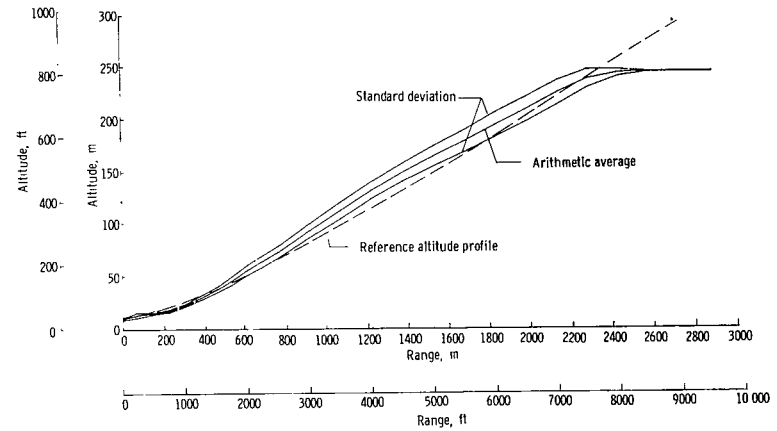


(d) All pilots, 140-knot ground-speed profile.

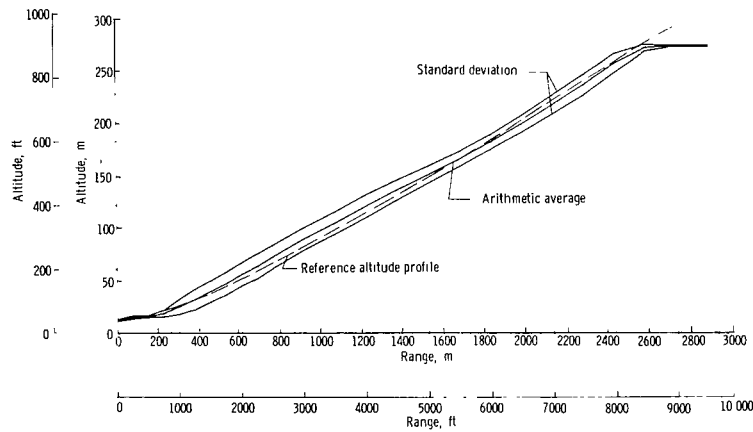
Figure 12.- Simulation results for altitude profiles.



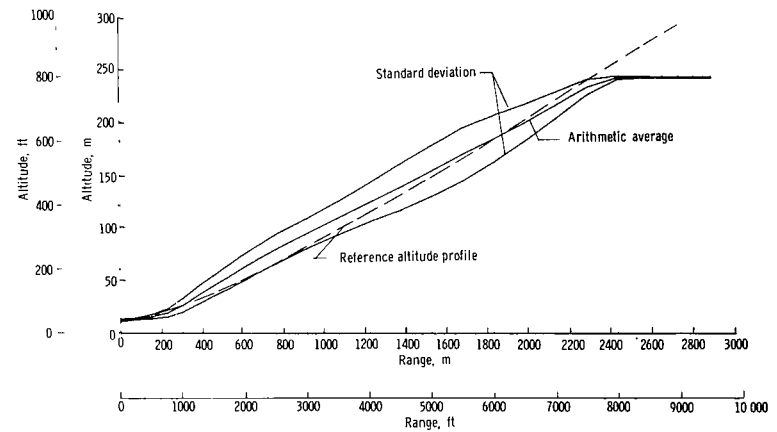
(e) Baseline pilot, 100-knot ground-speed profile.



(f) Baseline pilot, 110-knot ground-speed profile.

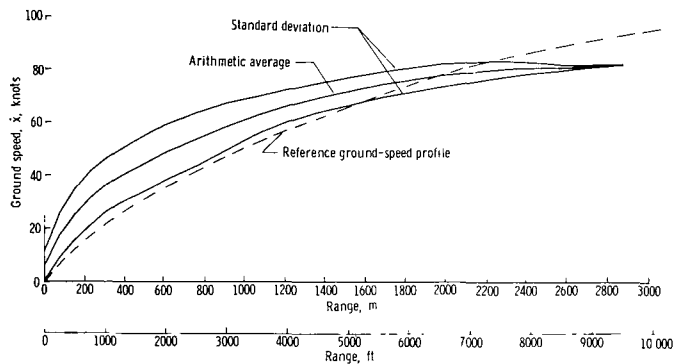


(g) Baseline pilot, 120-knot ground speed profile.

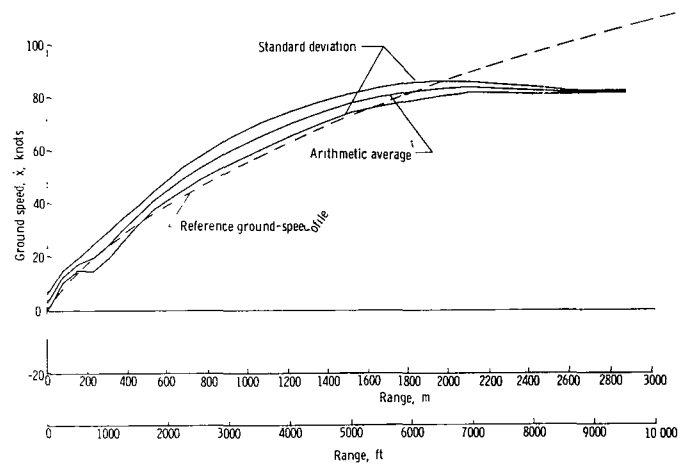


(h) Baseline pilot, 140-knot ground-speed profile.

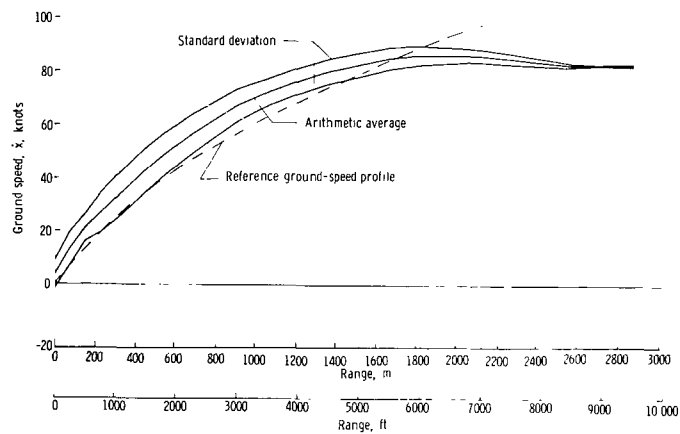
Figure 12.- Concluded.



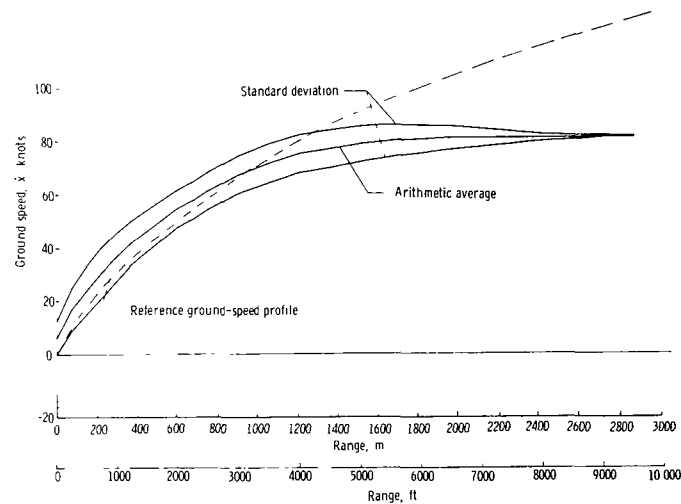
(a) All pilots, 100-knot ground-speed profile.



(b) All pilots, 110-knot ground-speed profile.

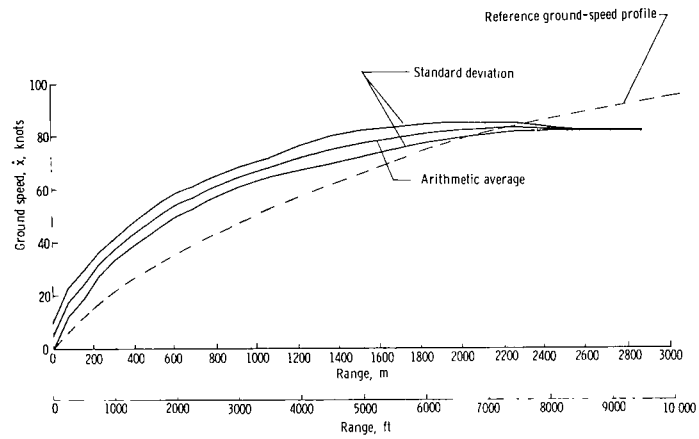


(c) All pilots, 120-knot ground-speed profile.

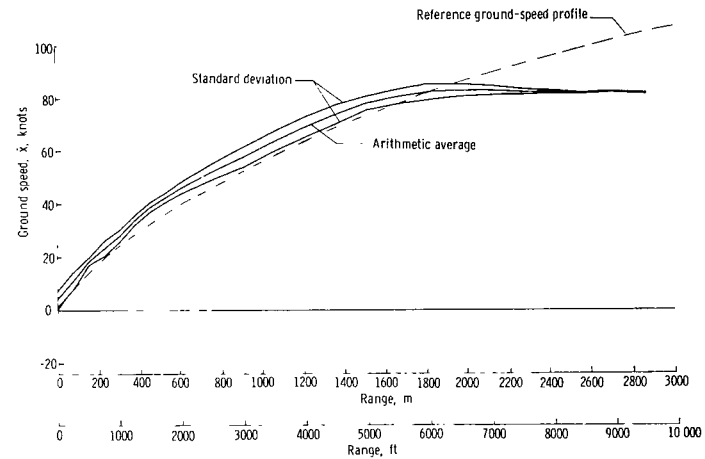


(d) All pilots, 140-knot ground-speed profile.

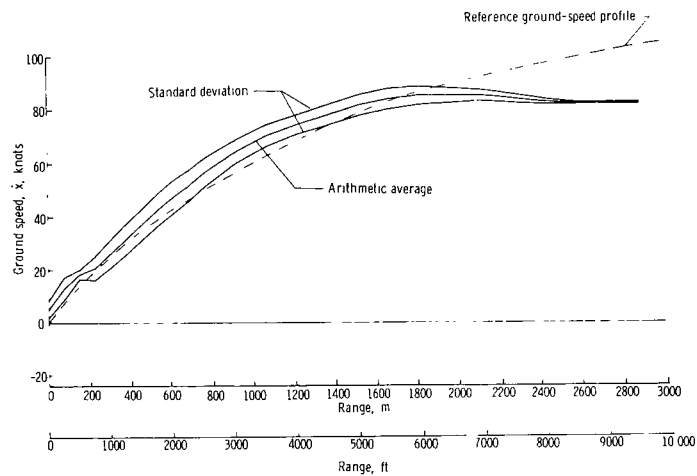
Figure 13.- Simulation results of ground-speed profiles.



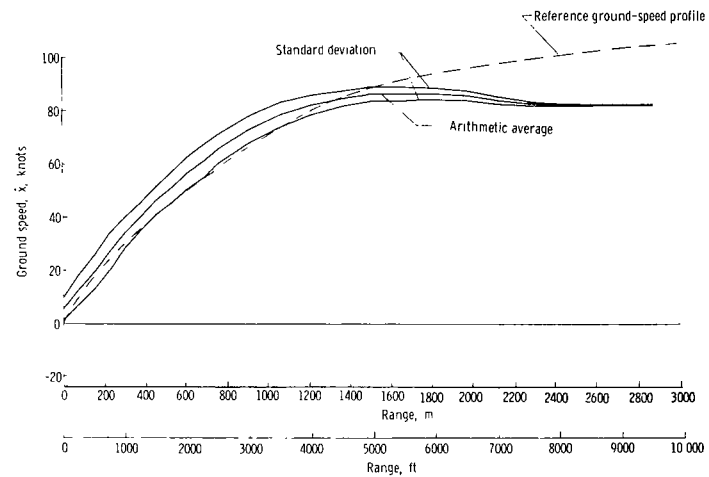
(e) Baseline pilot, 100-knot ground-speed profile.



(f) Baseline pilot, 110-knot ground-speed profile.

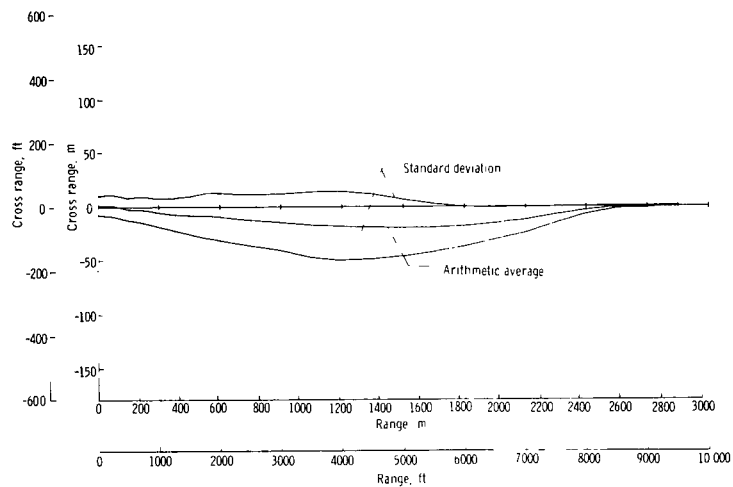


(g) Baseline pilot, 120-knot ground-speed profile.

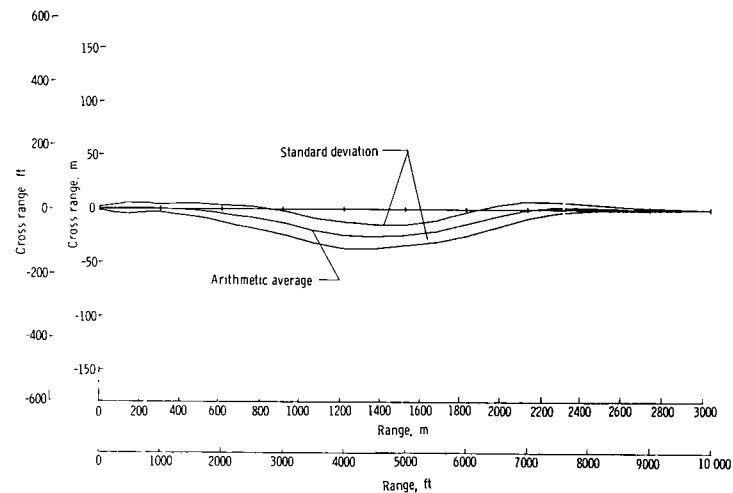


(h) Baseline pilot, 140-knot ground-speed profile.

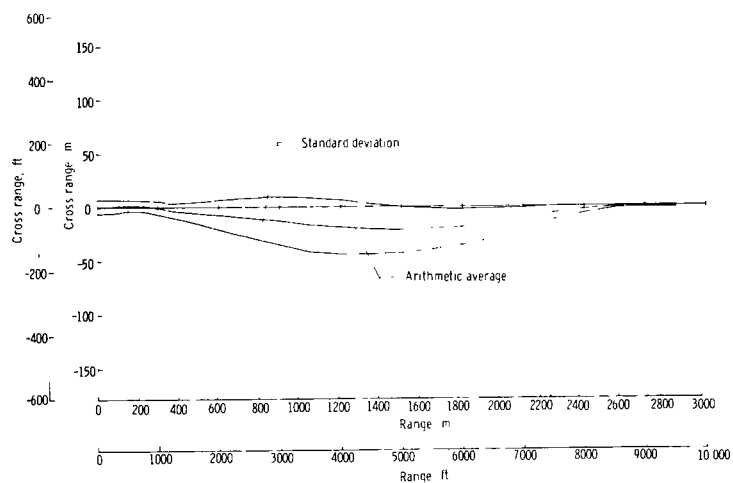
Figure 13.- Concluded.



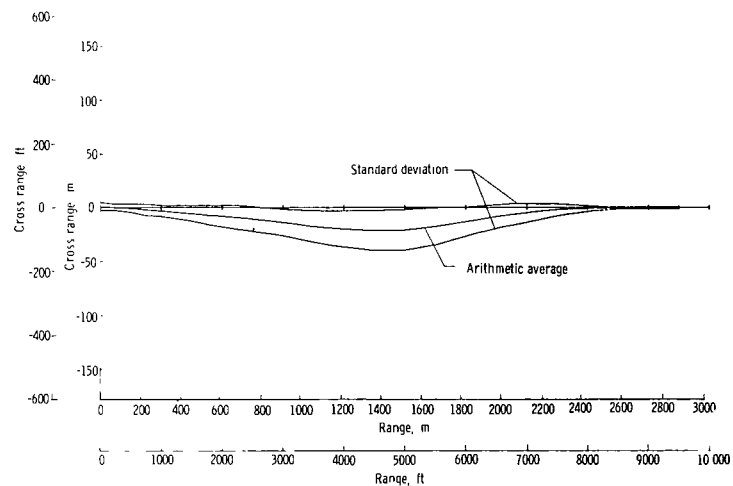
(a) All pilots, 100-knot ground-speed profile.



(b) All pilots, 110-knot ground-speed profile.

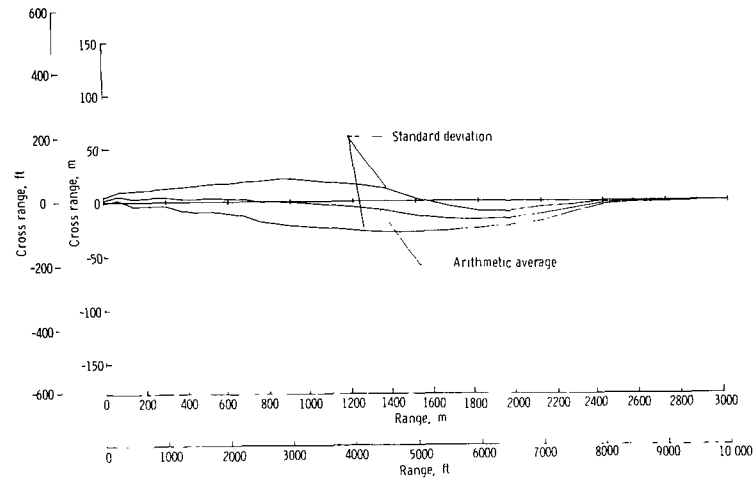


(c) All pilots, 120-knot ground-speed profile.

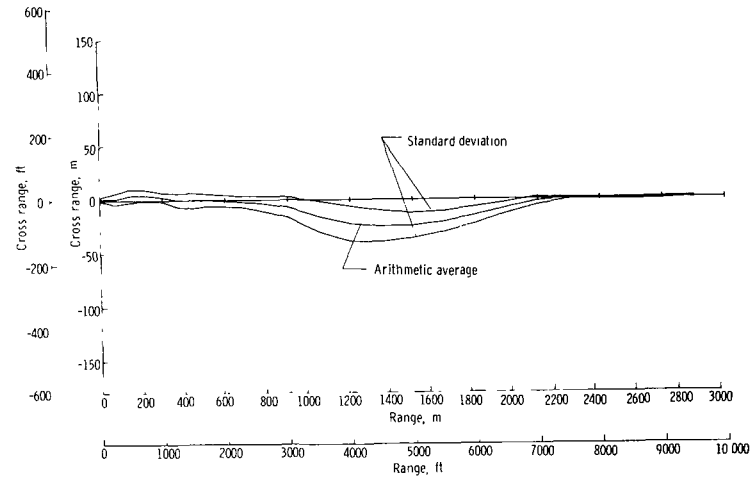


(d) All pilots, 140-knot ground-speed profile.

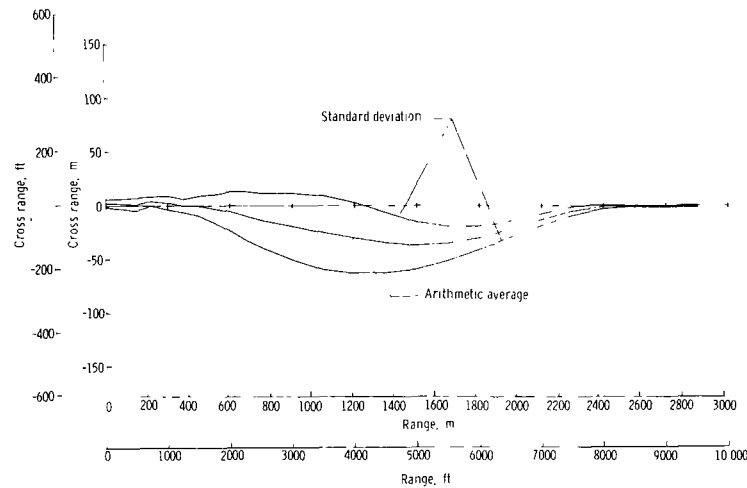
Figure 14.- Simulation results of cross-range profiles.



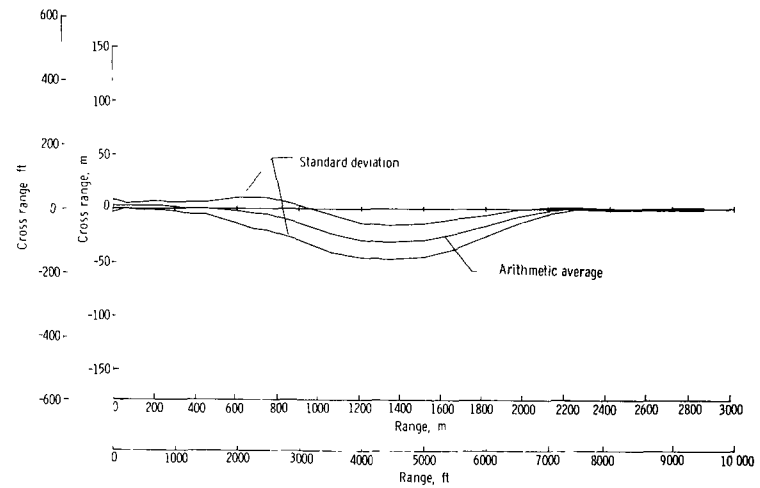
(e) Baseline pilot, 100-knot ground-speed profile.



(f) Baseline pilot, 110-knot ground-speed profile.

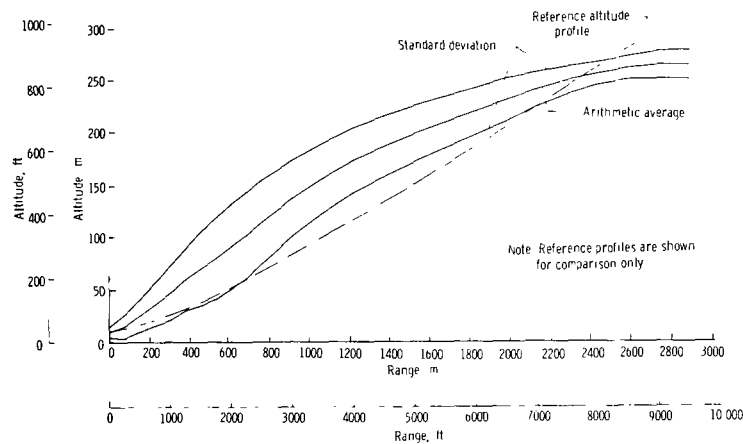


(g) Baseline pilot, 120-knot ground-speed profile.

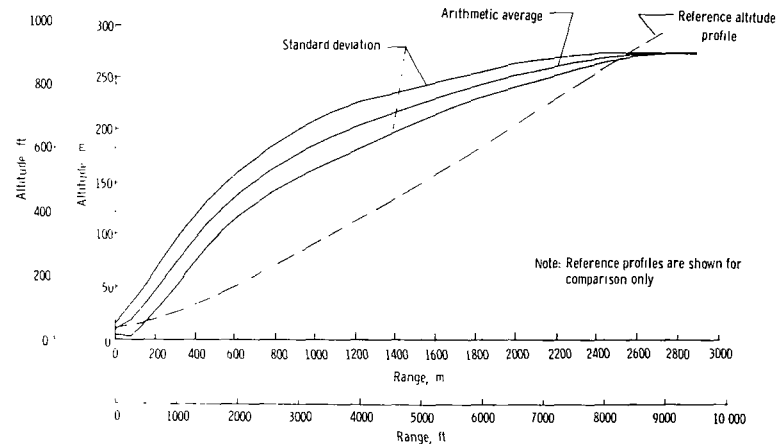


(h) Baseline pilot, 140-knot ground-speed profile.

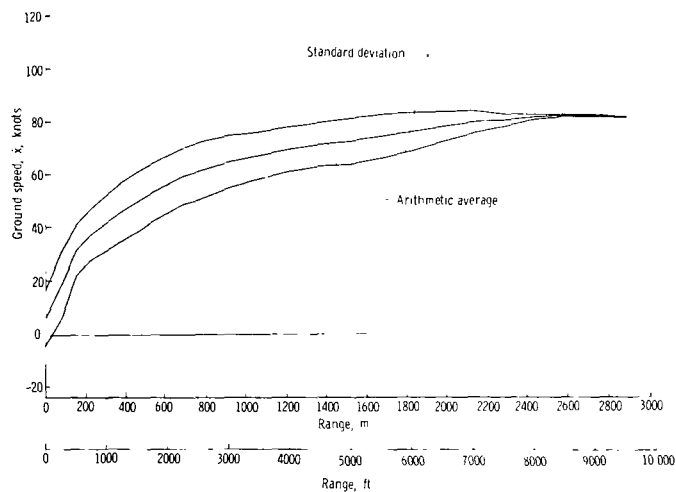
Figure 14.- Concluded.



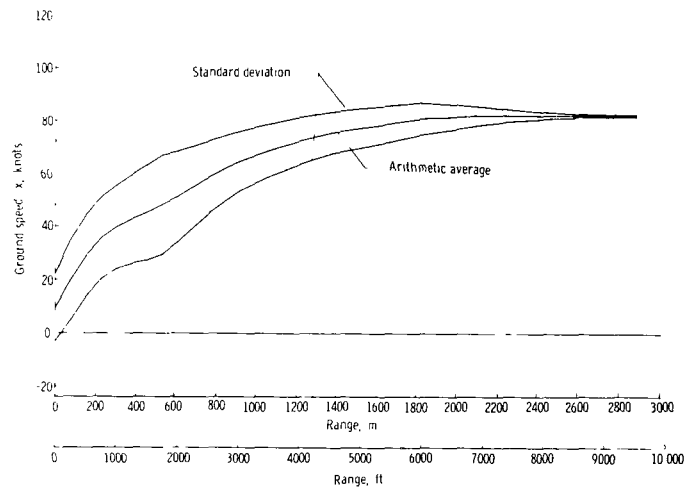
(a) Altitude profile for all pilots.



(b) Altitude profile for baseline pilot.

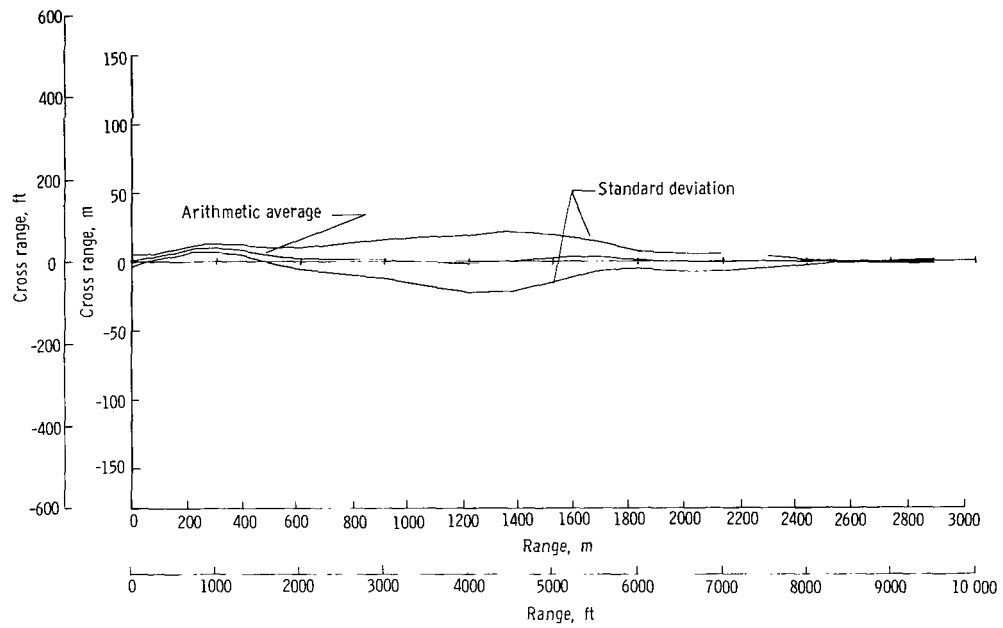


(c) Ground-speed profile for all pilots.

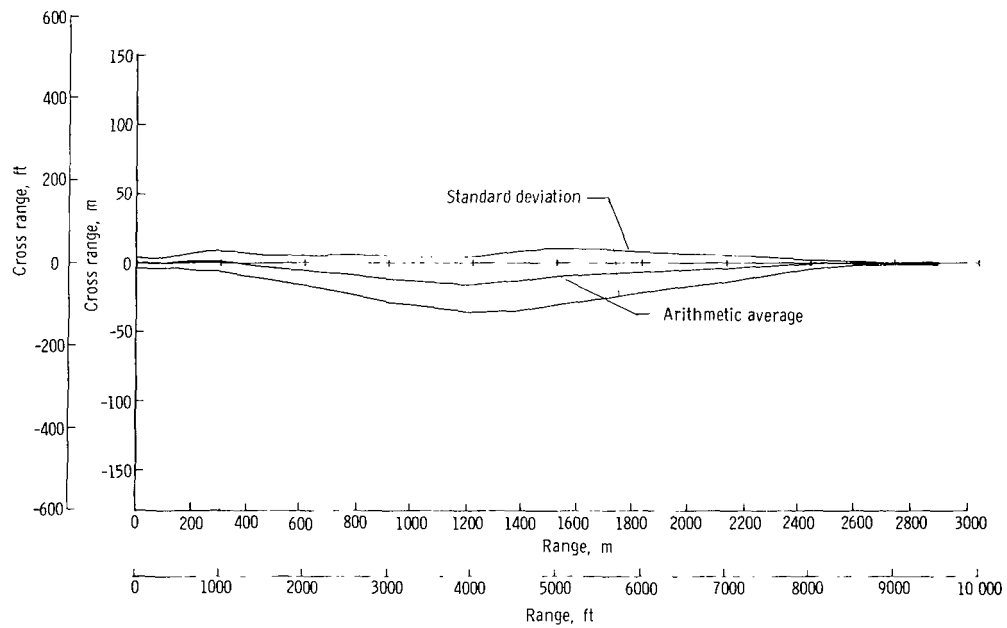


(d) Ground-speed profile for baseline pilot.

Figure 15.- Simulation results without the API.



(e) Cross-range profile for all pilots.



(f) Cross-range profile for baseline pilot.

Figure 15.- Concluded.

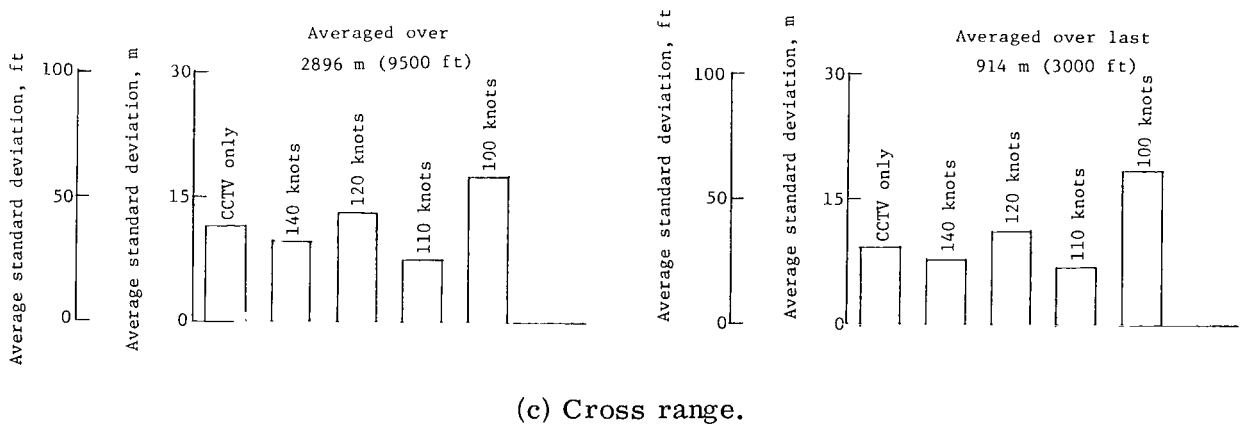
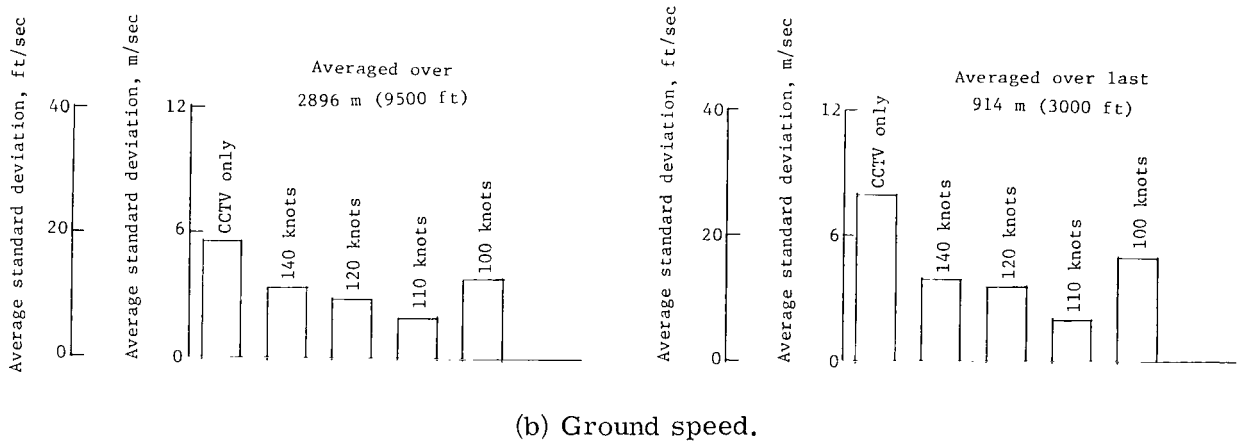
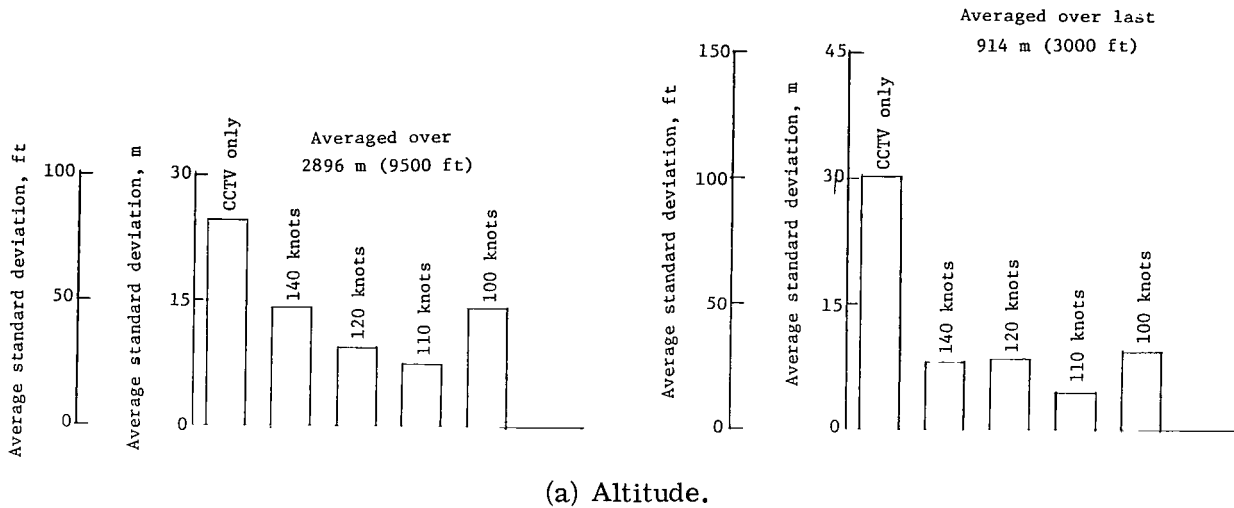
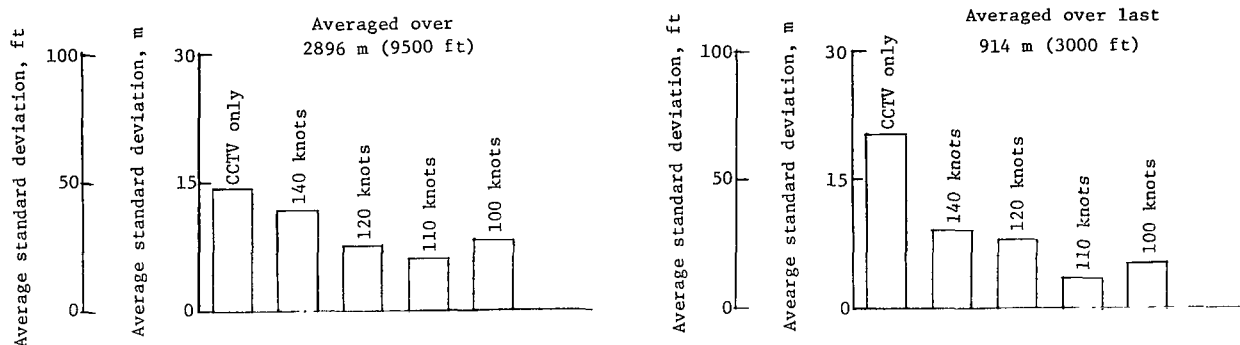
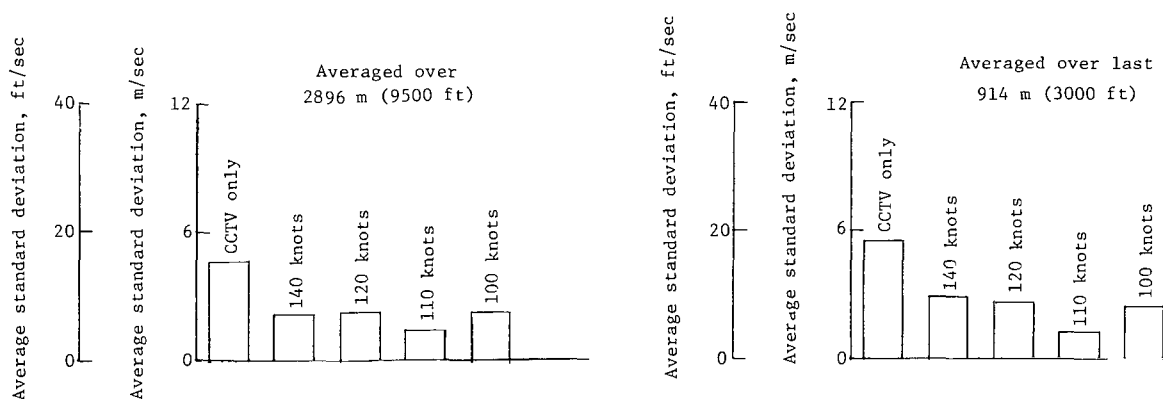


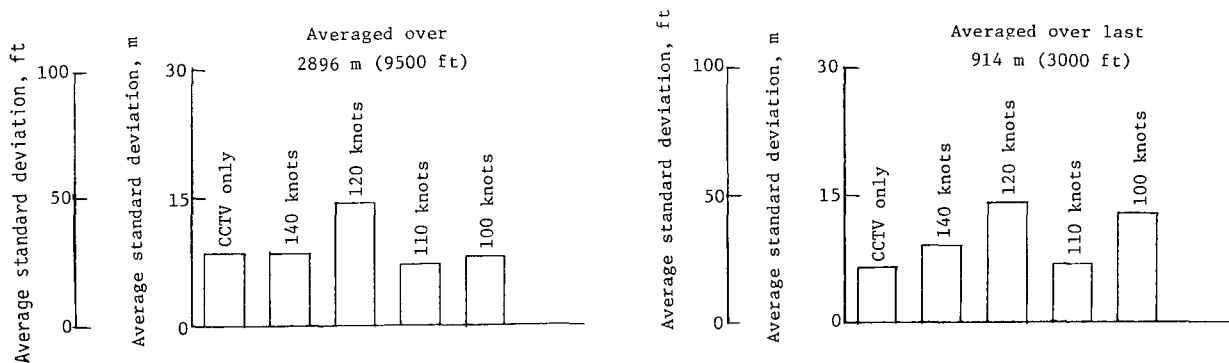
Figure 16.- Average standard deviation from simulation results for all pilots.



(a) Altitude.

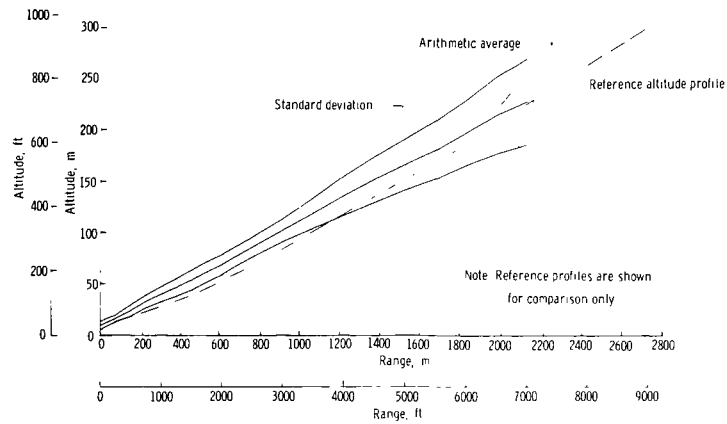


(b) Ground speed.

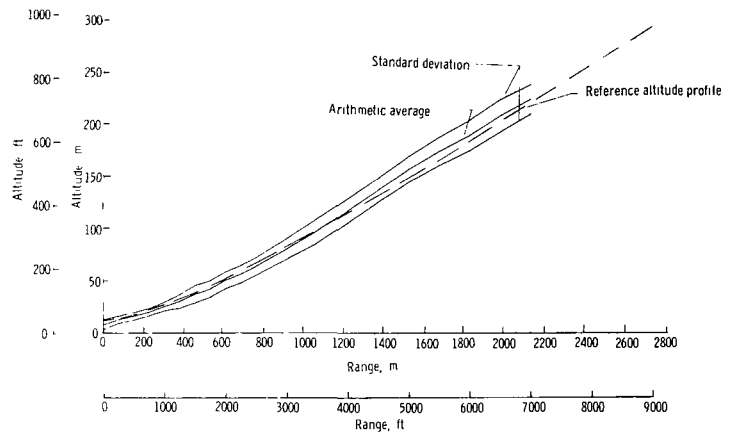


(c) Cross range.

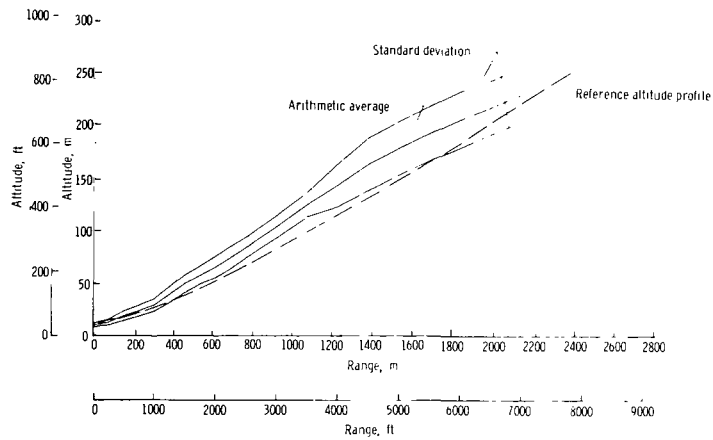
Figure 17.- Average standard deviation from simulation results for baseline pilot.



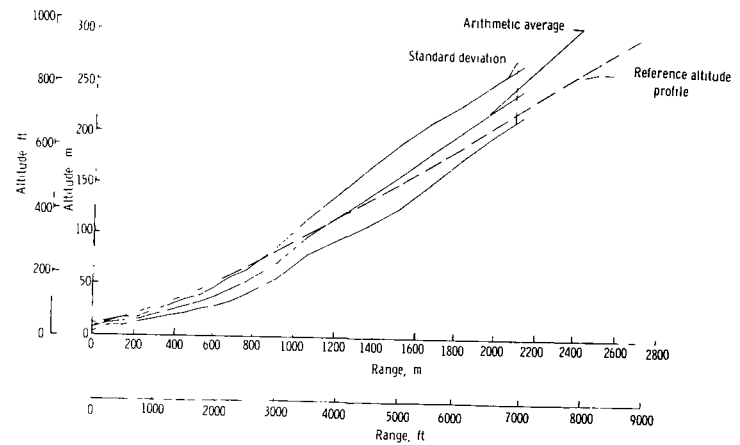
(a) Pilot A without the API.



(b) Pilot A with the API.

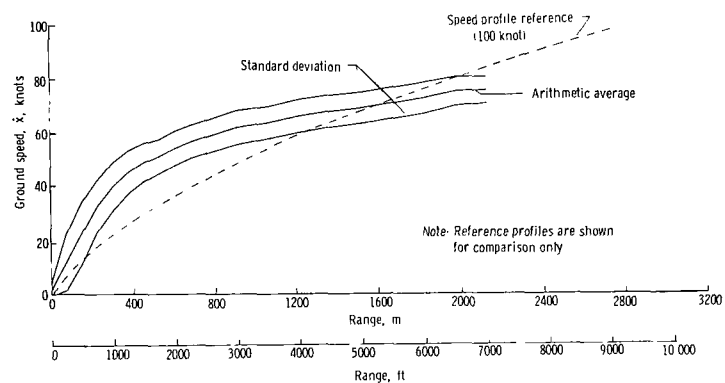


(c) Pilot B with the API.

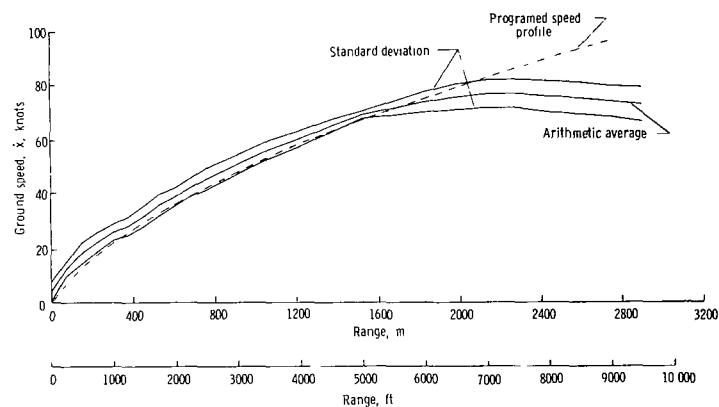


(d) Pilot E with the API.

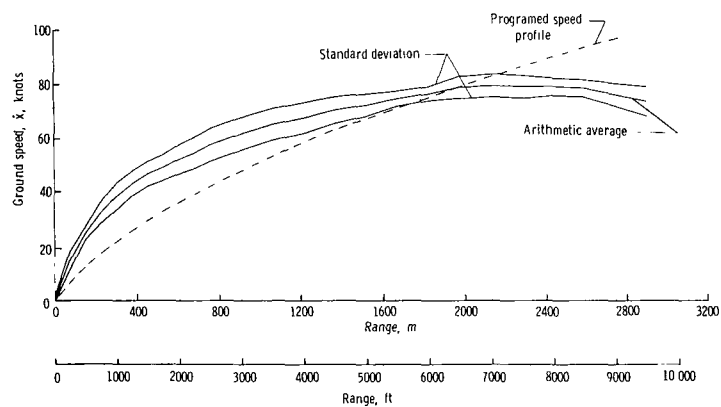
Figure 18.- Flight results of altitude profiles.



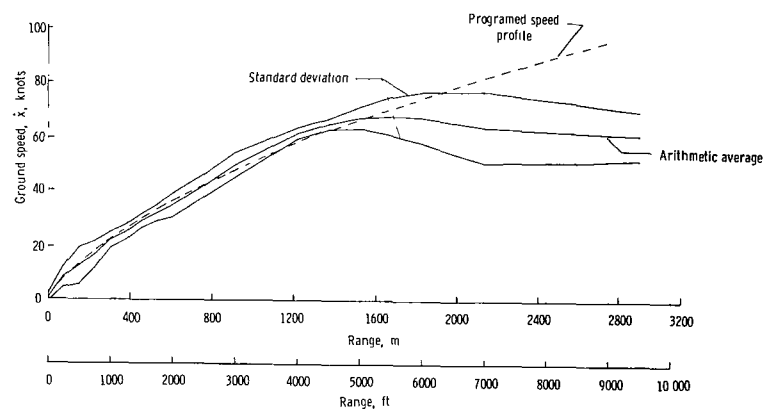
(a) Pilot A without the API.



(b) Pilot A with the API.

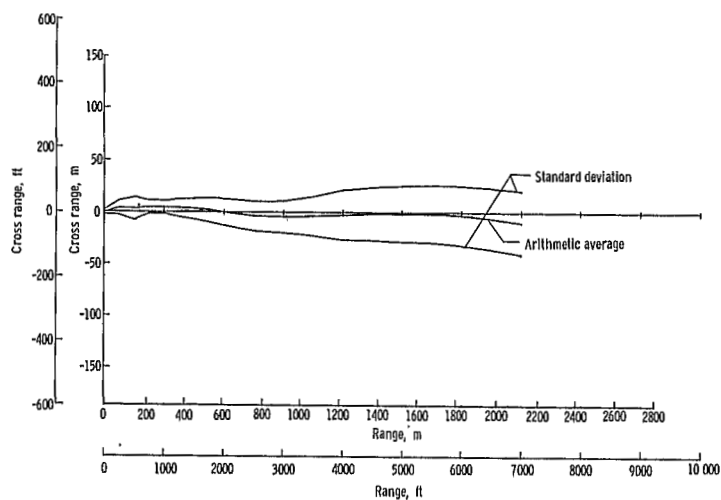


(c) Pilot B with the API.

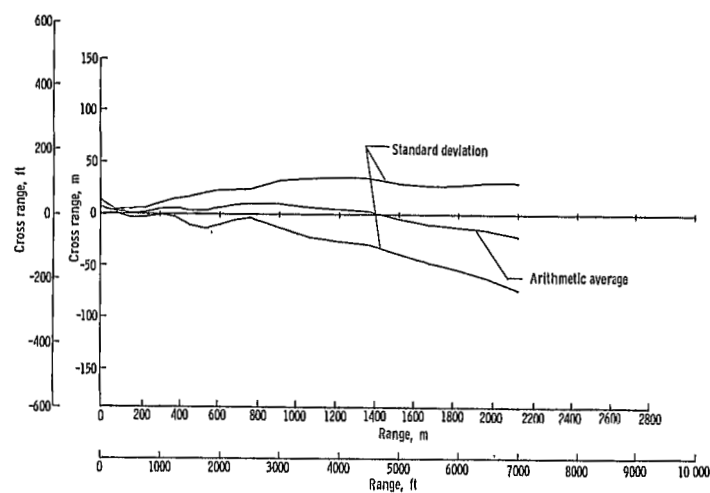


(d) Pilot E with the API.

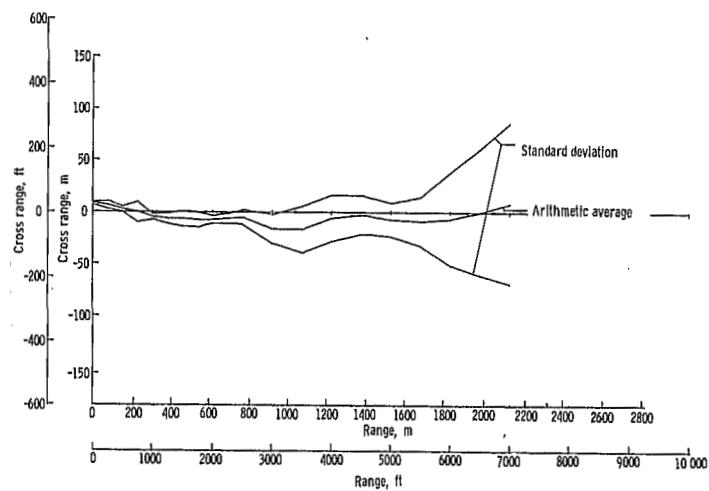
Figure 19.- Flight results of ground-speed profiles.



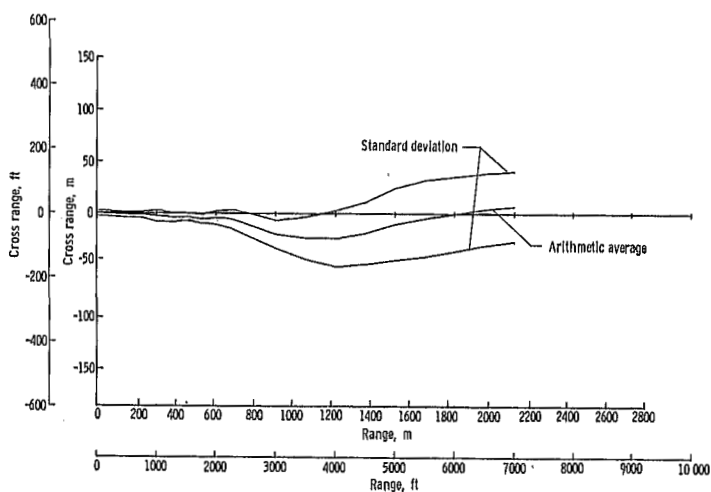
(a) Pilot A without the API.



(b) Pilot A with the API.



(c) Pilot B with the API.



(d) Pilot E with the API.

Figure 20.- Flight results of cross-range profiles.

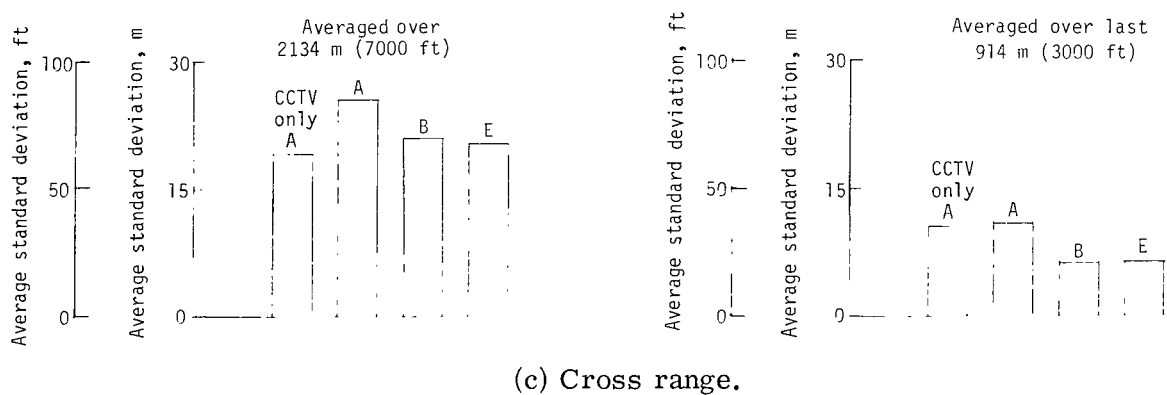
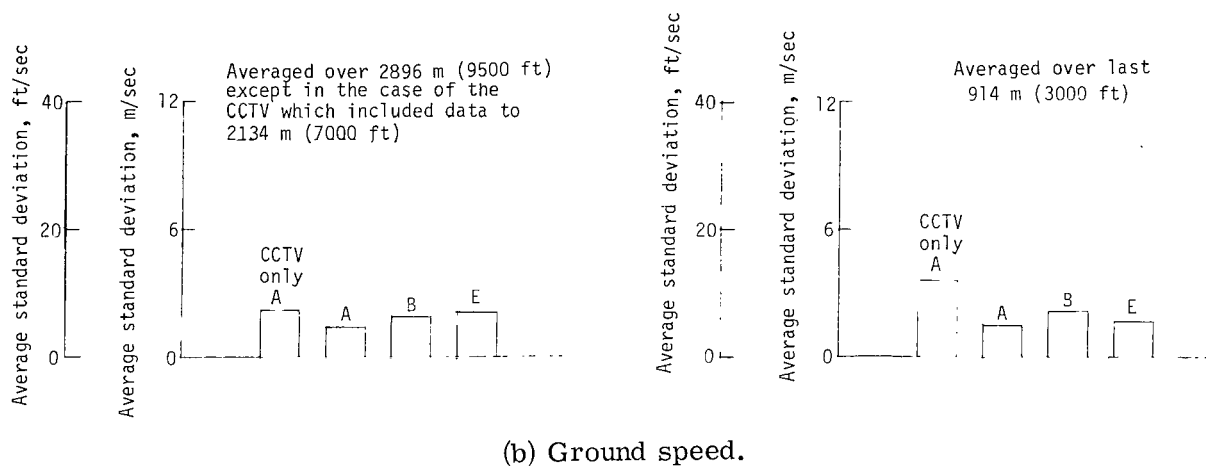
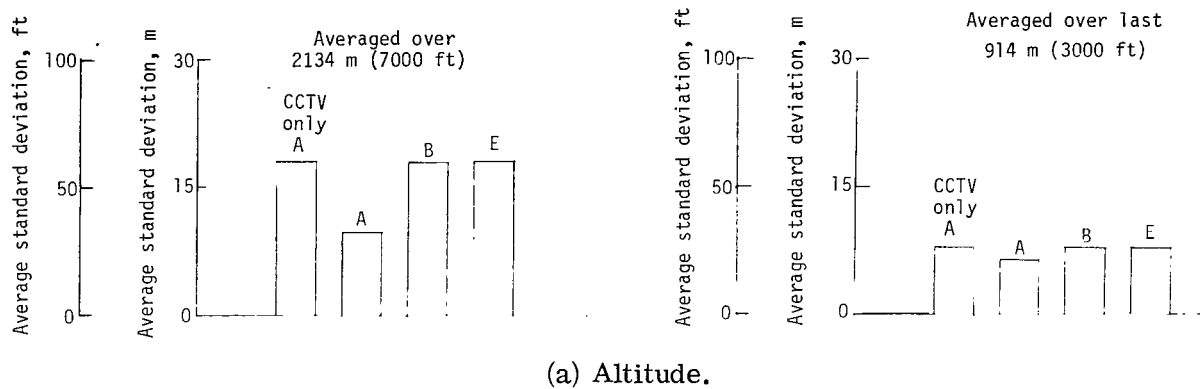
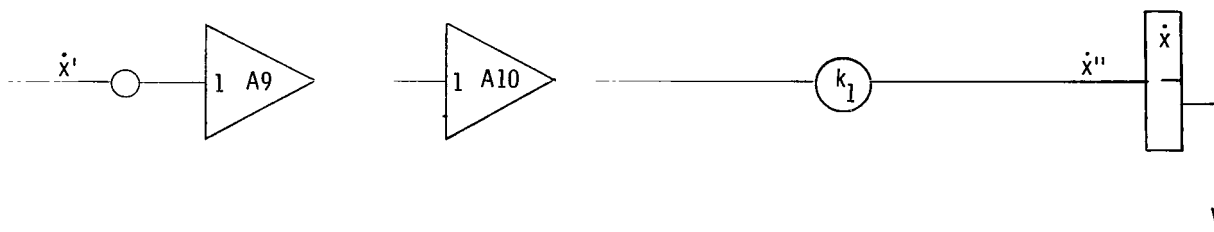
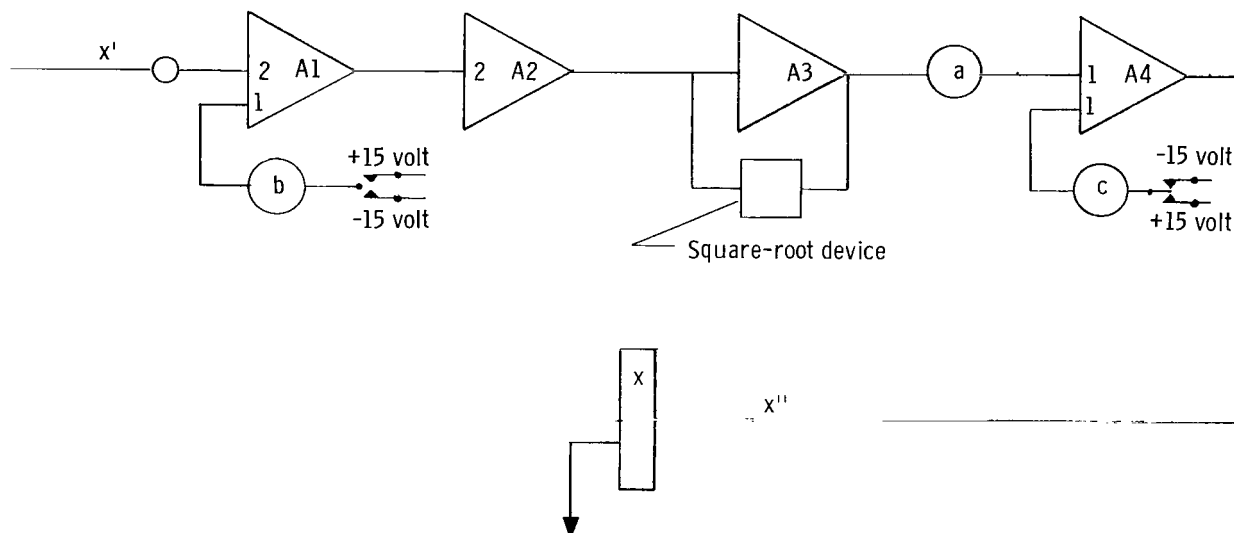


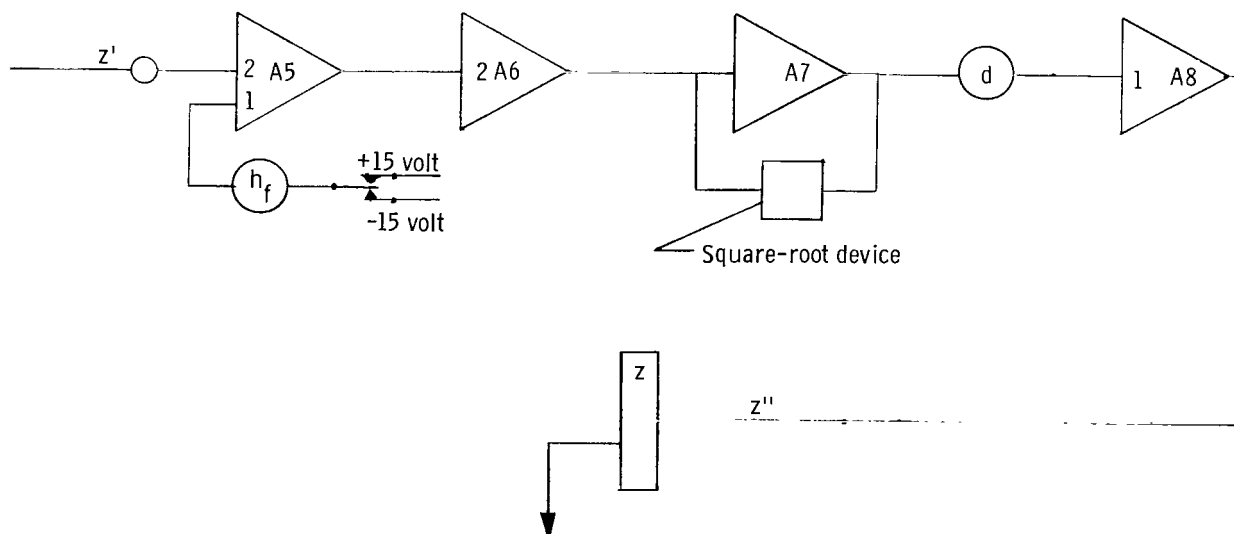
Figure 21.- Average standard deviation from flight results.



(a) Ground-speed channel.

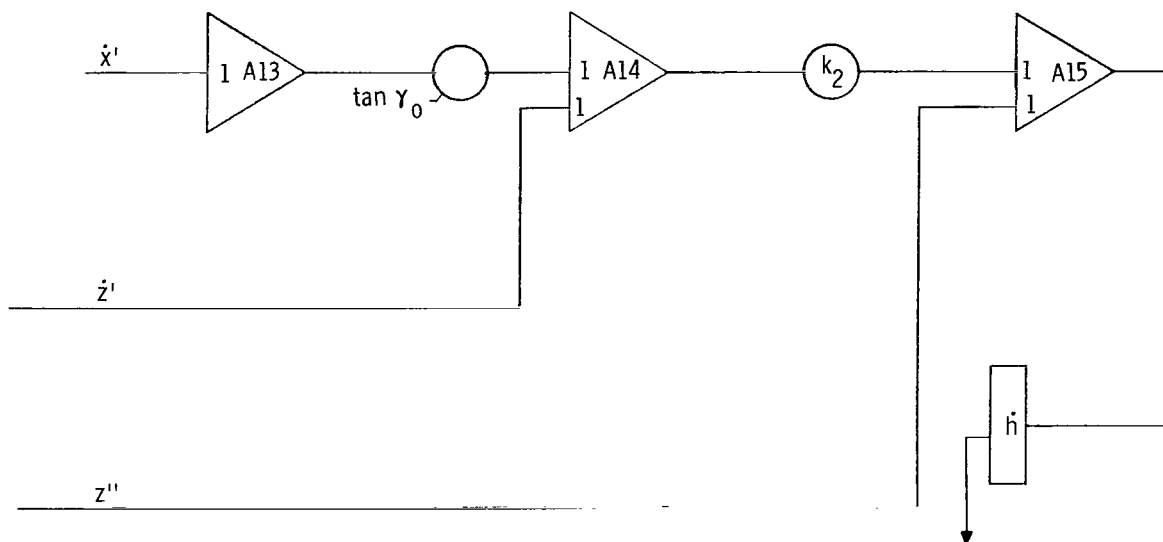


(b) Range channel.

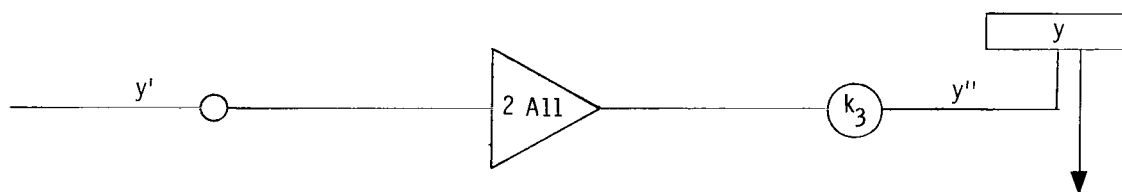


(c) Altitude channel.

Figure 22.- Signal processing diagrams.



(d) Rate-of-climb-error channel.



(e) Cross-range channel.

Figure 22.- Concluded.



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